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TECHNOLOGY ASSESSMENT OF SEQUENCING BATCH REACTORS

by

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16. ABSTRACT

The innovative and alternative technology provisions of the Clean Water Act of 1977 (PL 95-217) provide financial incentives to communities which use wastewater treatment alternatives that reduce costs of energy consumption over conventional systems. Some of these technologies have been only recently developed and are not in widespread use in this country. In an effort to increase awareness of the potential benefits of such alternatives and to encourage their implementation where applicable, the Municipal Environmental Research Laboratory has initiated this series of Emerging Technology Assessment reports. This document discusses the applicability and economic feasibility of utilizing Sequencing Batch Reactors as a viable alternative to conventional continuous flow activated sludge facilities for the treatment of municipal wastewater.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The innovative and alternative technology provisions of the Clean Water Act of 1977 (PL 95-217) provide financial incentives to communities which use wastewater treatment alternatives that reduce costs of energy consumption over conventional systems. Some of these technologies have been only recently developed and are not in widespread use in this country. In an effort to increase awareness of the potential benefits of such alternatives and to encourage their implementation where applicable, the Water Engineering Research Laboratory has initiated this series of Emerging Technology Assessment reports. This document discusses the applicability and economic feasibility of utilizing Sequencing Batch Reactors as a viable alternative to conventional continuous flow activated sludge facilities for the treatment of municipal wastewater.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

As a result of the innovative and alternative technology provisions of the Clean Water Act of 1977, the U.S. Environmental Protection Agency (EPA) has initiated a series of technology assessments dealing with the three major objectives of these provisions:

1. To incorporate more cost-effective and energy-efficient systems in publicly owned treatment works than current traditional practice.

2. To encourage innovative and alternative processes that provide for the reclamation and reuse of wastewater.

3. To encourage the utilization of recycling techniques, land treatment, and new and improved methods of joint municipal and industrial treatment.

The technology assessments have been coordinated through the Construction Grants program for a number of "emerging" technologies which were developed through the encouragement of the U.S. EPA because of potential applications in municipal wastewater treatment practice. The assessments are intended to evaluate both the current status and capabilities of the "emerging" technologies. This technology assessment report provides a thorough analysis of the Sequencing Batch Reactor.

The Sequencing Batch Reactor (SBR) is a fill and draw activated sludge system. Each tank in the SBR system is filled during a discrete period of time and then operated in a batch treatment mode. After treatment, the mixed liquor is allowed to settle and the clarified supernatant is drawn from the tank. If the time required for a tank to fill is very long compared to the time provided for batch treatment, the SBR behaves like a conventional completely mixed activated sludge facility. If the opposite is true, the SBR behaves like a nominal plug flow system. In fact by properly designing tank volumes and aeration policies, the SBR can simulate any conventional continuous flow activated sludge system from contact stabilization to extended aeration and can operate with either biological phosphorus or nitrogen removal or with BOD_5 and SS removal alone.

The major essential difference between the SBR and conventional continuous flow activated sludge is that each SBR tank carries out the functions of equalization, aeration and sedimentation in a time sequence rather than in the conventional space sequence of continuous flow systems where these functions are carried out in separate tanks. One advantage of a time orientation is flexibility of operation, in that the relative tank volumes

dedicated to, say, aeration and sedimentation, can be redistributed easily by adjusting the mechanism which controls the time (and, therefore, share of the total volume) planned for either function. In a conventional continuous flow facility the relative tank volumes are fixed and cannot be shared or redistributed easily.

Because of the flexibility associated with working in time rather than in space, the SBR can be operated as either a labor intensive, low energy, high sludge yield system or a minimal labor, high energy, low sludge yield system for essentially the same physical plant. The actual operating policy used can be adjusted in accordance with prevailing economic conditions by simply modifying the settings of the control mechanism. Labor, energy and sludge yield can also be traded off with initial capital costs.

While considerable bench-scale analysis of SBR operation has been conducted, the only thoroughly examined full-scale SBR was a demonstration study of a two-tank SBR which took place over a period of 20 months at the facilities of the Town of Culver in Indiana. The average flow during SBR operating periods was 1340 m^3/d, the loading varied from 0.2 to 0.4 kg BOD_5/d/kg MLVSS on an aeration time adjusted basis and the sludge age ranged between 15 and 45 days. Phosphorus was removed chemically by adding either ferric chloride or alum. During the first twelve months of operation, the effluent BOD_5, SS and phosphorus concentrations from both tanks averaged less than 10 g/m^3, 8 g/m^3 and 0.5 g/m^3 respectively. During the last four months nitrification and denitrification operating stategies were implemented. SBR operation during this period achieved similar effluent BOD_5, SS and phosphorus as above; as well as effluent ammonium and nitrite plus nitrate nitrogen concentrations of 1.1 g/m^3 and 1.3 g/m^3 respectively. Biological nitrogen removal of inorganic nitrogen during this period was roughly 90%.

A cost and energy analysis which compared the SBR to both the oxidation ditch and conventional activated sludge for volumetric flow rates of 379, 1893, 3785 and 18,925 m^3/d was conducted. The total installed capital costs for the SBR and oxidation ditch were similar, with the SBR being slightly less costly. As compared to the conventional activated sludge system, the SBR costs were roughly 20 percent less for all systems tested. While the energy analysis showed the SBR to be as much as 13.5 percent more efficient than the oxidation ditch and of equivalent efficiency when compared to conventional activated sludge, a much more exhaustive analysis must be conducted before any real benefit in energy savings can be claimed. An interesting feature of the SBR, however, is that the energy input can be varied over a rather wide range without seriously impairing the effluent quality. This benefit results from the fill and draw nature of the system and probably cannot be matched by most continuous flow activated sludge systems.

Based on the cost and energy results reported herein and the obvious flexibility of the SBR, the potential for the SBR penetration in both present and future markets is expected to be quite high. The extent of penetration however, will depend upon actual costs and energy needs of the first group of new SBR facilities to be constructed and operated.

The SBR is a new technology that will be more foreign to potential users in the United States than will most all other new technologies because it is not a continuous flow system. Until the novelty of periodic operation becomes accepted as a viable treatment alternative, implementation of the SBR will be slow. In addition, because it is a new technology, the SBR will likely be misused by individuals not realizing its limitations or not understanding the SBR well enough to design the system properly. Finally, sewage treatment plant operators are not familiar with fill and draw operation and, as a result, will require special training. In spite of these potential difficulties, the net benefits from the SBR are expected to be appreciable.

The report was submitted in fulfillment of Contract No. 68-03-3055, Roy F. Weston, Inc., by Robert L. Irvine of the University of Notre Dame, under the sponsorship of the U.S. EPA. This report covers the period of April, 1982 to November, 1982 and the work was completed as of November, 1983.

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SECTION 1

TECHNOLOGY DESCRIPTION

INTRODUCTION

The Sequencing Batch Reactor (SBR) is a fill and draw activated sludge system. Each tank in the SBR system is filled during a discrete period of time and then operated in a batch treatment mode. After treatment, the mixed liquor is allowed to settle and the clarified supernatant is drawn from the tank. If the time required for a tank to fill is very long compared to the time provided for batch treatment, the SBR behaves like a conventional completely mixed activated sludge facility. If the opposite is true, the SBR behaves like a nominal plug flow system. In fact by properly designing tank volumes and aeration policies, the SBR can simulate any conventional continuous flow activated sludge system from contact stabilization to extended aeration.

The major essential difference between the SBR and conventional continuous flow activated sludge is that each SBR tank carries out the functions of equalization, aeration and sedimentation in a time sequence rather than in the conventional space sequence of continuous flow systems where these functions are carried out in separate tanks. One advantage of a time orientation is flexibility of operation, in that the relative tank volumes dedicated to, say, aeration and sedimentation, can be redistributed easily by adjusting the mechanism which controls the time (and, therefore, share of the total volume) planned for either function. In a conventional continuous flow facility the relative tank volumes are fixed and cannot be shared or redistributed easily.

Because of the flexibility associated with working in time rather than in space, the SBR can be operated as either a labor intensive, low energy, high sludge yield system or a minimal labor, high energy, low sludge yield system for essentially the same physical plant. The actual operating policy used can be adjusted in accordance with prevailing economic conditions by simply modifying the settings of the control mechanism. Labor, energy and sludge yield can also be traded off with initial capital costs.

The SBR is easily operated with or without biological phosphorus and nitrogen removal by providing anaerobic, anoxic and aerobic conditions in a proper time sequence without, of course, employing the sludge recycle stra-

tegies common to the conventional biological nutrient removal facilities. This technology assessment report evaluates past and current studies on biological removal of nutrients, biological oxygen demand (BOD) and suspended solids (SS) in the SBR which are currently under various stages of development and application.

DETAILED TECHNICAL DESCRIPTION

The cycle for each tank in a typical SBR is divided into the five discrete periods of FILL, REACT, SETTLE, DRAW and IDLE as is shown in Figure 1. Central in this figure is one tank which is pictured in each of the five periods of one cycle. Also shown is the percent of the maximum liquid volume and total cycle time that may be dedicated to each period and the purpose of and aeration policy used for each period. A detailed discussion of each period of the SBR is provided below along with a description of typical process equipment and hardware that may be associated with each.

FILL. The influent to the tank may be either raw wastewater (screened and degritted) or primary effluent. The influent may be either pumped in or allowed to flow in by gravity. When more than one tank is used and the influent is added by gravity, some device (e.g. an adjustable weir or an automated valve) must be operated such that the flow is diverted to one tank or the other.

The tank may be an earthen ditch, an oxidation ditch, a rectangular basin or any other concrete or metal type structure. During FILL the influent wastewater is added to activated sludge which remained in the tank from the previous cycle. The liquid volume increases from the initial level (shown to be 25 percent of the total in Figure 1) to the maximum of 100 percent. Actually the initial volume may be as great as 70 percent or more of the maximum, and the period can be designed to terminate before the maximum level is reached by limiting the FILL time to a predetermined maximum. The initial volume is determined based on a number of factors including desired loading and detention time. The time of FILL is shown to be 25 percent of the total cycle time in Figure 1 but will be more or less depending upon the extent of diurnal variations in the hydraulic flow rate. The full-scale SBR demonstration study at Culver, Indiana (1) had an average time of FILL of approximately 50 percent of the total average cycle time of six hours. The initial volume at Culver averaged roughly 60 percent of the maximum liquid volume (460 m^3).

Virtually any aeration system (e.g. diffused, floating mechanical, or jet) can be used. As will be described during a later chapter, the extent to which the substrate is consumed during FILL is critical to the development of organisms with good settling characteristics. In addition, biological nutrient removal depends upon alternating conditions of low and high dissolved oxygen (D.O.). As a result, the aeration system must be able to provide a range of mixing intensities from zero to complete agitation. In addition, it may be desirable to provide the flexibility of mixing without aeration. At Culver, where jet aeration was used (1), mixing only (no aeration) was provided

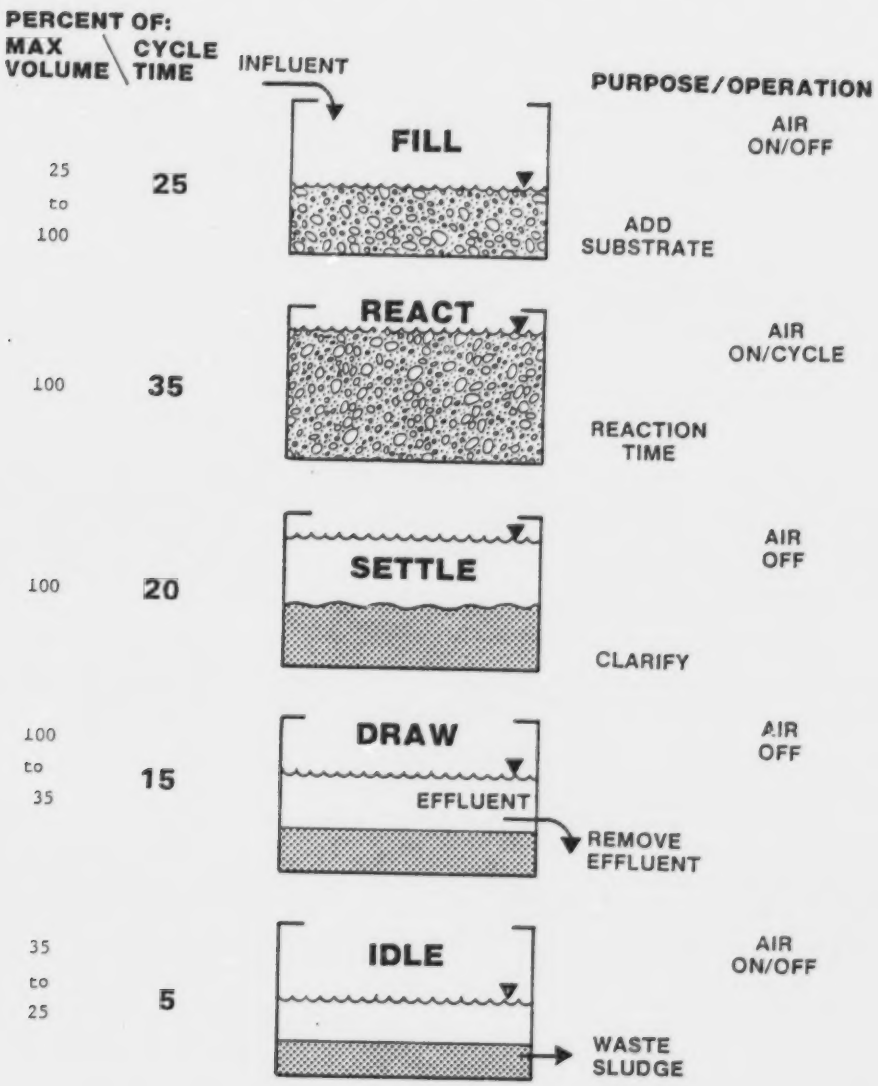


FIGURE 1. TYPICAL SBR OPERATION FOR ONE CYCLE (5)

during the first half of FILL, and full aeration during the remainder of FILL. This was accomplished by installing a float switch about half way between the minimum and maximum liquid volumes which, when tripped, signalled the controller to activate the aeration system. Either level sensing devices or timers could be used to switch the aerators on and off as desired.

FILL is terminated when the tank is either full (as determined by a level indicator) or when a maximum time for FILL is reached. The wastewater flow is then diverted to another tank in the SBR system.

REACT. Reactions which were initiated during FILL are completed during REACT. As in FILL, alternating conditions of high and low D.O. may be required. While Figure 1 suggests that the liquid level remains at the maximum throughout REACT, sludge wasting can take place during this period as a simple means for controlling the sludge age. For example, the sludge age in days would be equal to the reciprocal of the fraction of the maximum liquid volume wasted each day. While 35 percent of the total cycle time is shown in Figure 1 to be dedicated to REACT this can vary from a low of zero to more than 50 percent. At Culver (1), the time in REACT was roughly 10 percent of the total.

The end of REACT may be dictated by a time specification (e.g. the time in REACT shall always be 1.5 hours) or a level controller. Use of the level controller is actually quite simple. In a two tank system, when the liquid level in the tank in FILL reaches some predetermined level, a signal is sent to the controller which cuts-off all mixing or aeration devices operating in the tank in REACT. In a three tank system a simple control which ends REACT in the first tank when the "second" tank ends FILL (or the "third" tank begins FILL) can be easily implemented.

SETTLE. In the SBR, solids separation takes place quiescently in a tank which may have a volume of more than ten times that of a secondary clarifier in a conventional continuous flow activated sludge plant. This major advantage results from the fact that the aeration tank serves as the clarifier during a period that no flows enter the tank. Because all of the activated sludge remains in the tank until some fraction must be wasted, there is no need for underflow hardware normally found in conventional clarifiers. In way of contrast, mixed liquor is continuously removed from a conventional activated sludge aeration tank and passed through the clarifiers only to have a major portion of the sludge returned to the aeration tank.

The time in SETTLE should be fixed between 0.5 and one hour so that the sludge blanket remains below the withdrawal mechanism during DRAW but does not rise (because of gas formation) before DRAW is completed. At Culver (1), the time in SETTLE was 45 minutes and was approximately 12.5 percent of the total cycle time.

DRAW. The withdrawal mechanism may take one of many forms. It may be as simple as a pipe fixed at some predetermined level with the flow regulated by either an automatic valve or a pump, depending upon the hydraulic grade line of the system. Alternatively an adjustable weir or a floating weir at or just beneath the liquid surface can be used. As with the fixed mounted pipe, discharge from the weir can be regulated by an automatic valve or a pump. At Culver (1), two types of floating weirs were used. Both used submersible pumps to activate withdrawal but in one case the pump floated with the weir and in the other case the pump was fixed to the back wall of the aeration tank.

The time dedicated to DRAW can range from five to more than 30 percent of the total cycle time. The time in DRAW, however, can not be overly extended because of possible problems with rising sludge. At Culver (1), DRAW accounted for approximately 12.5 percent of the total cycle time.

IDLE. After DRAW, the tank is ready to receive additional wastewater but because the tank which is in FILL may not have reached the maximum liquid level, the tank just completing DRAW must wait. The period between DRAW amd FILL is termed IDLE. This time can, however, be used effectively. As Figure 1 shows, sludge can be wasted during IDLE. The frequency of sludge wasting can range between once each cycle to once every two to three months depending upon system design. At Culver (1), sludge was wasted during one of the four cycles each day by pumping settled sludge (approximately 0.1 percent of the maximum liquid volume) over a ten to fifteen minute period.

Aeration and/or mixing can be provided or not during IDLE depending upon whether aerobic digestion or denitrification were desired. Neither aeration nor mixing was used at Culver (1) during IDLE.

Alternatively, IDLE can be eliminated altogether by terminating FILL in the tank receiving the wastewater as soon as the tank in DRAW reaches the minimum liquid level. This would not force sludge wasting to take place during REACT since wasting can easily take place during either the end of SETTLE or any time during DRAW.

Overall control of the SBR is accomplished with level sensors and a timing device. At Culver (1), a microprocessor served as the timing device.

Before completing this section, a hybrid period, including aspects of both FILL and DRAW will be described. This hybrid period, called FILL(1) during the Culver study (1), recognized that a tank may be in DRAW when the liquid level in the tank in FILL reaches the maximum. In this case, the tank in DRAW can terminate withdrawal and begin a normal FILL. Alternatively, FILL and DRAW can overlap. Specifically the tank in DRAW can continue effluent withdrawal even though the influent wastewater has been diverted to that tank. In order to protect the quality of the effluent during this hybrid period called FILL(1), a baffle wall can be installed at the inlet end of the tank so as to minimize short circuiting. The mixing and aeration devices

must, of course, be kept off and the total time allowed for FILL(1) can be limited to a predetermined time. By adding the notion of FILL(1) to the design of the SBR, the overall system capability is readily expanded. However, because of potential problems with short circuiting and a concommitant reduction in effluent quality, the frequency of FILL(1) occurrence and the maximum time allowed for each FILL(1) event should be severely restricted.

COMMON PHYSICAL MODIFICATIONS

The SBR system can employ one or more parallel sets of tanks with each set of tanks having a common cycle. Theoretically there is no limit to the size of each tank or of the number of tanks in a set.

The SBR system with just one tank (or set of tanks) would be quite unusual for a normal domestic waste situation but not all that uncommon for day schools, amusement parks and for industries which operate for eight to fifteen hours each day with little or no flow generated during the remaining hours (2). In this case, a second tank would be unnecessary since FILL would end naturally because of the absence of wastewater flow. Clearly, REACT, SETTLE and DRAW would have to be completed before the flow resumed.

A two tank SBR system was operated at Culver (1) and will be described in detail later. In such a system, the time for REACT, SETTLE and DRAW in one tank must be less than or equal to the time required to fill the other tank. FILL(1) can be used to relax this constraint.

An SBR with three sets of tanks is probably the practical limit for such systems. While it can be shown that the total volume (sum of all tanks used) of an SBR decreases with the number of sets of tanks employed, the incremental reduction is minimal for sets greater than three. In addition, the complexity of operation increases as the number of sets increases. As a result, except under quite unusual circumstances, only one, two or three sets of tanks would be recommended.

SECTION 2

DEVELOPMENT STATUS

GENERAL

Research on the SBR has been sponsored in part by the National Science Foundation (NSF) (3,4) and the United States Environmental Protection Agency's (U.S.EPA) Municipal Environmental Research Laboratory (MERL) (5). The bulk of this research effort has been conducted during the last seven years at the University of Notre Dame at an expenditure level of more than one million dollars.

The investigations can be broadly divided into two parts. The first was to establish a basic understanding of both the microbiological aspects and operating characteristics of the SBR. The second was to identify potential user markets and to familiarize the users with the SBR and its capabilities. The discussion which follows is a comprehensive summary of the findings from these investigations and others.

HISTORICAL USE OF FILL AND DRAW REACTORS

The overwhelming use of continuous flow activated sludge systems in the United States was an important factor limiting acceptance of the SBR as it was developed during the 1970's. In this regard, two factors are worthy of note. First, the SBR is no more than an activated sludge system which operates in time rather than in space. As a result, the periodic (i.e. fill and draw) nature of SBR operation simply expands the spectrum of treatment that is possible from conventional continuous flow activated sludge systems alone. Second, fill and draw treatment is not a new technology. Beginning with the first activated sludge systems investigated at the turn of this century and continuing sporadically through the 1960's, fill and draw systems had been used with notable success. The account which follows traces the early history of fill and draw systems. A much more extensive summary was prepared by Burke (6) and should be consulted by those wishing more detail.

With one exception, sewage treatment studies between 1884 and 1912 used either chemical precipitation or coarse media filters or a combination of the two in fill and draw tanks. Aeration was sometimes employed but often without improvement in the overall treatment. The one exception was reported in 1893 by Sir Thomas Wardle (7) who stated: "A distinctive feature of the process (a fill and draw reactor without either chemical

addition or filter media) is that the precipitated impurities which accumulate at the bottom of the tank form a medium in conjunction with air to clarify the inflowing foul water." Wardle's studies were, however, overlooked, and it wasn't until the now famous Manchester Experiments reported on by Arden and Lockett (8,9) in 1914 and 1915 that the term activated sludge was coined for the settled matter that was retained in their bench-scale fill and draw reactors.

Full-scale implementation of the Manchester Experiments were conducted at Salford, England in 1914 by Melling (10) and Duckwork (11). Two 83 m^3 tanks employing an average cycle of seven hours (0.75 hour FILL, three hour REACT, two hour SETTLE, one hour DRAW and 0.25 hour IDLE) were used to treat 303 m^3 of sewage each day. Effluent quality was quite good and was similar to that of a continuous flow system operated in parallel. In 1915, a full-scale fill and draw system was operated in Milwaukee, Wisconsin (12,13,14) with a one hour FILL, 3.5 hour REACT, 0.5 hour SETTLE and one hour DRAW. Nearly complete suspended solids removal was reported. Later comparisons between fill and draw and continuous flow treatment revealed no differences in basic operating characteristics.

Between 1914 and 1920 many additional full-scale fill and draw systems were operated (6). In almost all cases, these fill and draw systems were converted to continous flow operation. This was done in spite of O'Shaugnessy's (15) observation in 1923 that "the time required to effect a given purification in the sewage liquor is twice as great when continuous methods of treatment are adopted as opposed to fill and draw."

The reason for the switch to continuous flow operation was summarized by Arden (16) in 1927. Three main disadvantages of fill and draw operation were cited. These were: (1) the high energy that must be dissipated during discharge of the treated effluent; (2) increased operator attention and (3) clogging of diffusers because of the periodic settlement of the sludge. As a result the cost of construction and operation of the fill and draw system was more than that of the continuous flow facilities. As will be discussed later, vast improvements in both aeration devices and control systems leaves these objections without basis.

The next serious effort to use fill and draw technology in the treatment of municipal wastewaters was reported by Pasveer in the late 1950's and early 1960's (17,18,19). (The reader should note that Hoover, Porges and their coworkers - see reference 20 as an example - developed a fill and draw system for treatment of dairy wastewaters in the early 1950's.) Pasveer's system (often referred to as the Pasveer ditch) differed from the earlier fill and draw systems and the SBR in that the influent wastewater was continuously supplied to the aeration tank (a closed loop shallow ditch) while the treated effluent was discharged periodically. Specific operation included FILL until a predetermined liquid level was reached, no REACT (the Pasveer system used just one tank), SETTLE by cutting off the mixing and aeration as soon as FILL was terminated but without the elimination of the influent wastewater, and, finally, DRAW which was actually FILL(1) as described in the first section because the influent wastewater was not diverted to another tank. The exclusive use of FILL(1) for discharge and

the absence of REACT results in a poorer effluent quality and sludge settleability than is generally achieved in the SBR.

The fill and draw Pasveer ditch was quite popular in Europe for a few years but, with the exception of those in Denmark, virtually all plants installed were soon converted to conventional continuous flow oxidation ditches of the variety used in the United States by adding a secondary clarifier. One reason for this change was simple. During SETTLE the mixed liquor suspended solids (MLSS) would continue to circulate around the oxidation ditch rather than settle. As a result, the discharge mechanism usually intercepted the sludge blanket before the end of DRAW. Other reasons include the exclusive use of FILL(1) and the absence of REACT.

In Denmark the first of these Pasveer ditches was installed in 1962 with more than 250 in operation by 1980 (21). Survival of the fill and draw system in Denmark was coupled to a rather dramatic change in operating strategy. Briefly this change involved adding additional aeration tanks, switching influent wastewater flow from one tank to another and supplying mixing and/or aeration to the tanks in an alternating fashion. In addition, mixed liquor periodically moves from one tank to another. In some versions a final clarifier is used. In others three aeration tanks are used with sedimentation taking place in the aeration tanks and a FILL(1) type of DRAW employed. These hybrid alternating facilities are marketed in Denmark by Akvadan-Harvey A/S and more information can be obtained by writing Krogshojvej 29, DK-2880 Bagsvaerd, Denmark. Because none of these systems are in the United States and because they are generally only distantly related to the SBR, no further description of them will be provided herein.

The fill and draw Pasveer ditch was also introduced in Australia in 1965 (22,23,24) but, unlike in Europe, survived with but one simple modification. Shortly after the beginning of SETTLE the rotating floating brush aerator is reactivated for approximately 45 seconds but rotated in a direction opposite of that used during aeration. This dissipates the energy which causes the mixed liquor to continue its circular motion during SETTLE. As a result, the MLSS settles as it should during SETTLE. In 1979 there were over 100 of these modified Pasveer ditches in operation in New South Wales, Australia. Current plants, however, are designed as deep (4 m rather than the shallow 2 m ditches) rectangular basins which use either submerged jet or floating verticle shaft aerators. These systems are marketed in Australia by Bio-Jet Industries PTY.LTD., Chatswood, N.S.W. 2067, Australia. The Sequencing Batch Reactor is marketed in the United States by SBR Technologies, Inc., P.O. Box 697, Niagara Falls, New York 14303.

BENCH AND PILOT-SCALE RESEARCH

Between 1967 and 1971 the first developmental studies on the SBR were conducted at Texas A and M University by Thomas P. Fox (25) under the direction of Robert L. Irvine. During the same period Irvine and Davis (26) designed the first full-scale SBR for the treatment of starch manufacturing wastewater. While the SBR hydraulically operates as simply as is noted in

SECTION 1. TECHNOLOGY DESCRIPTION, the process aspects of the system are far more critical to design than the hydraulics and were not sufficiently understood during this early period of development. As a result research on SBRs was halted until 1976 when the NSF (3,27) sponsored a three year study at the University of Notre Dame entitled "Application of Sequencing Batch Reactors for Treatment of Municipal and Industrial Wastewaters." During this time bench-scale and pilot-scale SBR systems were operated which led to a more basic understanding of process dynamics and to the first full-scale SBR facility (1).

The first efforts from the NSF study were a reanalysis of Fox's early work (28) and a comparison of the SBR with a conventional completely mixed continuous flow activated sludge system (29). Fox (28) showed that reasonably simple stoichimetric and kinetic expressions could be used to describe SBR operation. The more extensive analyses which took place during the NSF studies, however, demonstrated the need for a much more detailed kinetic scheme.

Nevertheless the comparative analysis (29) was undertaken using the assumptions based on Fox's work. Figure 2 depicts two important observations. First, the total volume of an SBR system for three of the hydraulic and concentration profiles tested decreased as the total number of tanks increased. The three profiles 1) constant flow and concentration, 2) flow and concentration varying in-phase in time as a sine function and, 3), flow and concentration varying in-phase as a parabola were analyzed for an average flow of 3785 m^3/d and an average concentration of 500 g/m^3. The second observation is that all SBR systems investigated were smaller than the largest continuous flow stirred reactor (CFSTR) system evaluated (the total volume for the flow and concentration being represented by an in-phase sine wave for an equalization tank, a CFSTR aeration tank and final clarifier). Another finding was that the total size of the SBR was quite insensitive to the final concentration of soluble substrate desired. Later analyses supported these qualitative findings but showed that the overall and instantaneous mass loading on the system has a dramatic impact on organisms selected and effluent suspended solids.

The next significant work was reported by Dennis and Irvine (30) in the February 1979 issue of the Journal of the Water Pollution Control Federation. In that issue, five other papers (2,31,32,33,34) described current research on SBRs and one paper summarized work that had been conducted on the fill and draw Pasveer ditch in Australia (24). A description of the major findings reported in this issue are summarized below.

Dennis operated three bench-scale SBRs with an eight hour cycle. Each SBR received the same mass of substrate (Trypticase Soy Broth, TSB) during a totally aerated FILL and each went through SETTLE, DRAW and IDLE in two hours, leaving the remaining six hours for FILL plus REACT. The time for FILL was two hours for one SBR, four hours for the second and five hours for the third. Although each system had the same sludge age and the same average loading, the systems differed markedly with respect to 1) the mass of oxygen consumed per unit mass of organisms present per hour as is shown in Figure 3, and 2) the settling rate of the MLSS in a one liter graduated

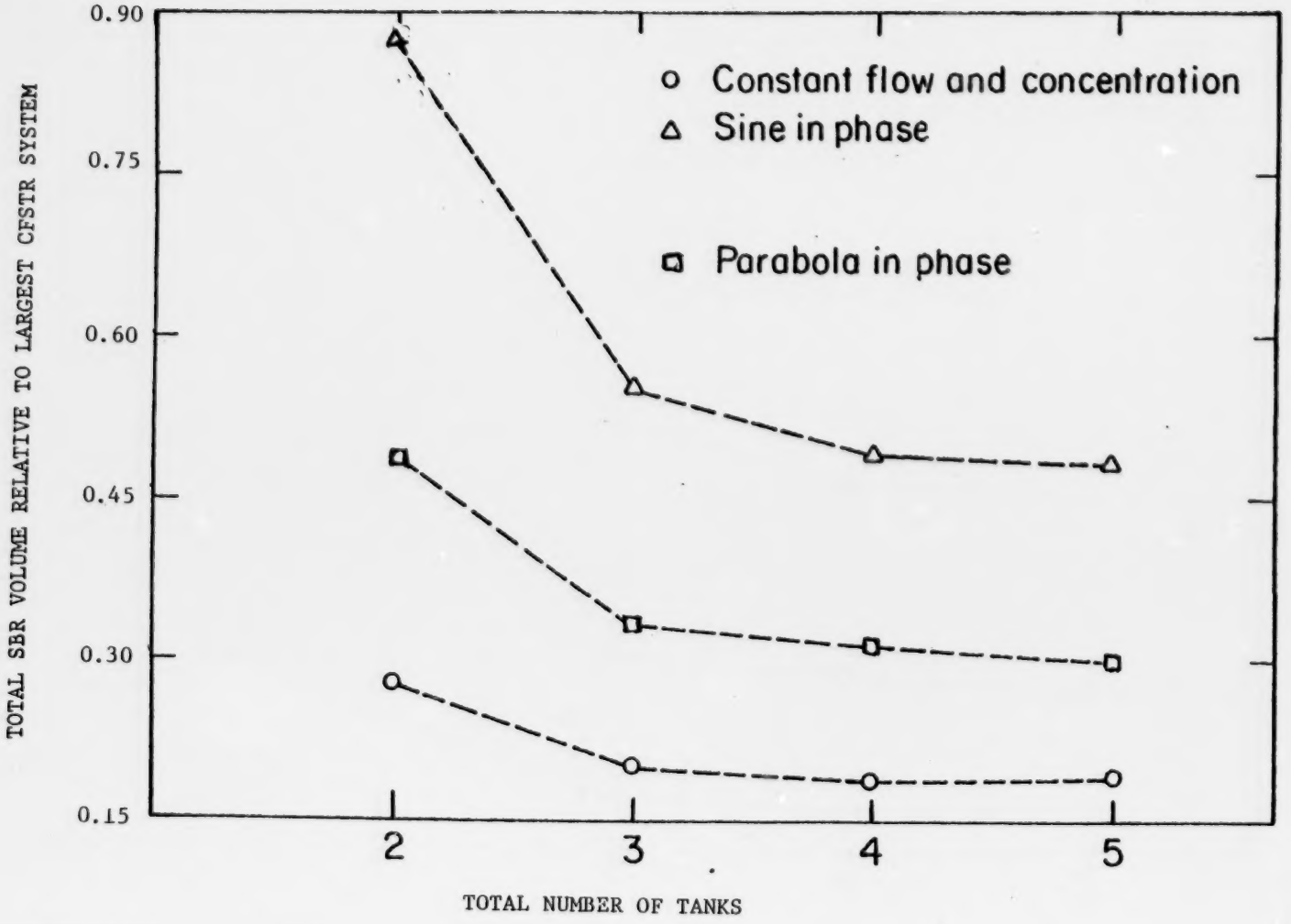


FIGURE 2. RELATIVE TOTAL VOLUME OF SEQUENCING BATCH REACTORS AS A FUNCTION OF NUMBER OF TANKS IN SYSTEM (29)

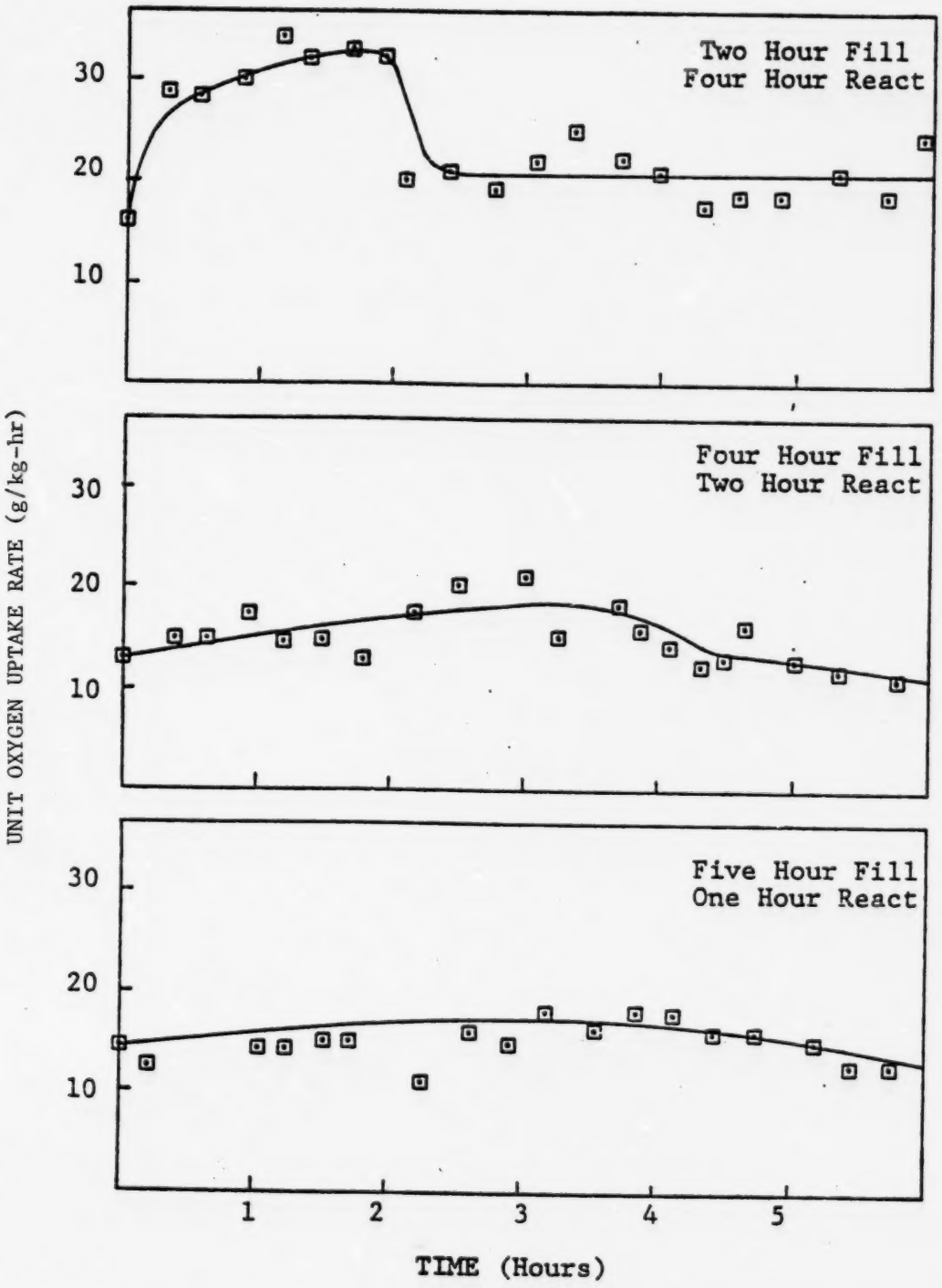


FIGURE 3. UNIT OXYGEN UPTAKE RATES FOR ALL SYSTEMS (30)

cylinder as is shown in Figure 4. These results ultimately led to the observations that high substrate concentrations help select for organisms with good settling characteristics. In this particular case the high substrate concentration could be inferred from Figure 3 from the high unit uptake rate for the two hour FILL reactor.

At this point in the bench-scale studies there was some concern over the possibility that domestic wastewaters may be too weak to support a good settling population in the SBR. At the same time preliminary cost analyses indicated that the extremely high oxygen uptake rates associated with elevated initial substrate concentrations resulted in excessive capital costs for the aeration equipment. These two problems were resolved simultaneously with the observation that the elevated initial substrate concentrations could be easily achieved by not aerating during some or all of FILL. Dennis (31) demonstrated that a partial period of mixing only tended to improve the settling characteristics of the mixed liquor. Miller and Irvine (2) and Palis and Irvine (35) used this notion to treat domestic wastewater with a lightly loaded single tank SBR (approximately 0.05 kg BOD/kg MLSS/d) with both good settling characteristics and nitrogen removal. Alleman (36) and Alleman and Irvine (37,38) used this principle to obtain both biological nitrogen and phosphorus removal in an SBR treating a synthetic waste (TSB).

Miller's system was operated with a 24 hour cycle with approximately ten hours devoted to FILL and twelve to REACT with two hours used for SETTLE, DRAW and IDLE (2). Roughly the first half of FILL was mixed without aeration. Aeration continued throughout the remainder of FILL into the first hour or two of REACT. The impact of such an operation on nitrogen removal is shown in Figure 5. Notice that the ammonium nitrogen increases when the air is off and is converted immediately to oxidized nitrogen as soon as the air supply is turned on. Denitrification is only partially achieved in this lightly loaded system. Palis (35), however, demonstrated that alternating periods of high and low D.O. during FILL of a similarly loaded SBR could ensure denitrification as is shown in Figure 6.

Alleman (36,37,38) was able to show the importance of a non-aerated (but mixed) FILL on the intracellular level of glycogen and the removal of oxidized nitrogen. As can be seen from Figure 7.1 oxidized nitrogen is produced during a three hour aerated REACT period from ammonia nitrogen and organic nitrogen which accumulates during FILL (these components not shown). During the same aerated REACT the soluble total organic carbon (TOC_S) is removed rapidly (see Figure 7.2) and glycogen increases (see Figure 7.3). During a mixed only REACT which occurs from the fifth to eighth hour the oxidized nitrogen leaves as nitrogen gas and the glycogen decreases to near background levels. Also shown in Figure 7.4 is the release of orthophosphorus during the anaerobic FILL and the ensuing reincorporation of phosphorus during the aerobic REACT as is common to the current biological phosphorus removal systems.

An interesting observation from Alleman's work is that even though the extracellular concentration of soluble substrate (TOCs in Figure 7.2) is

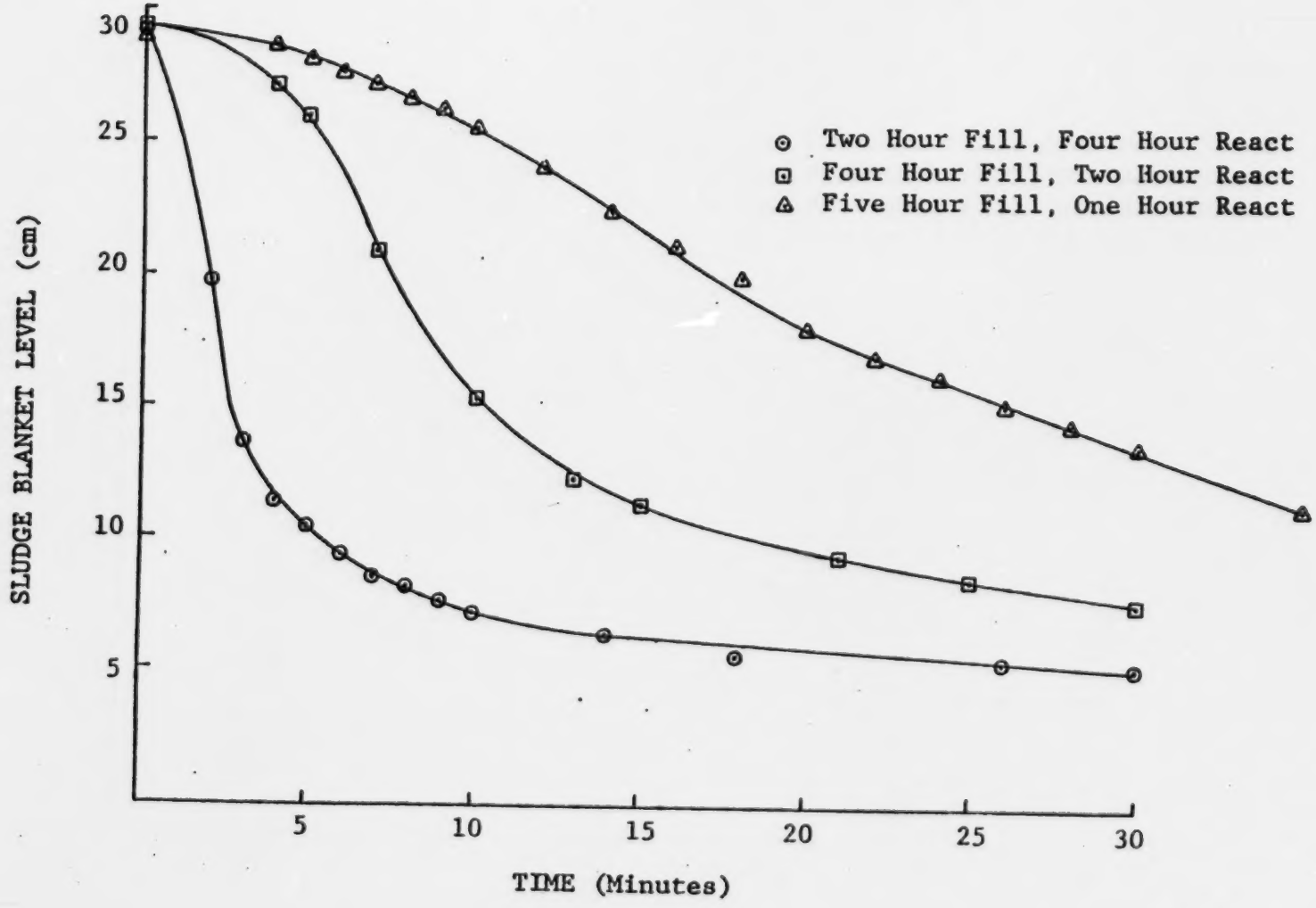


FIGURE 4. SLUDGE BLANKET LEVEL VS. TIME FOR ALL SYSTEMS (30)

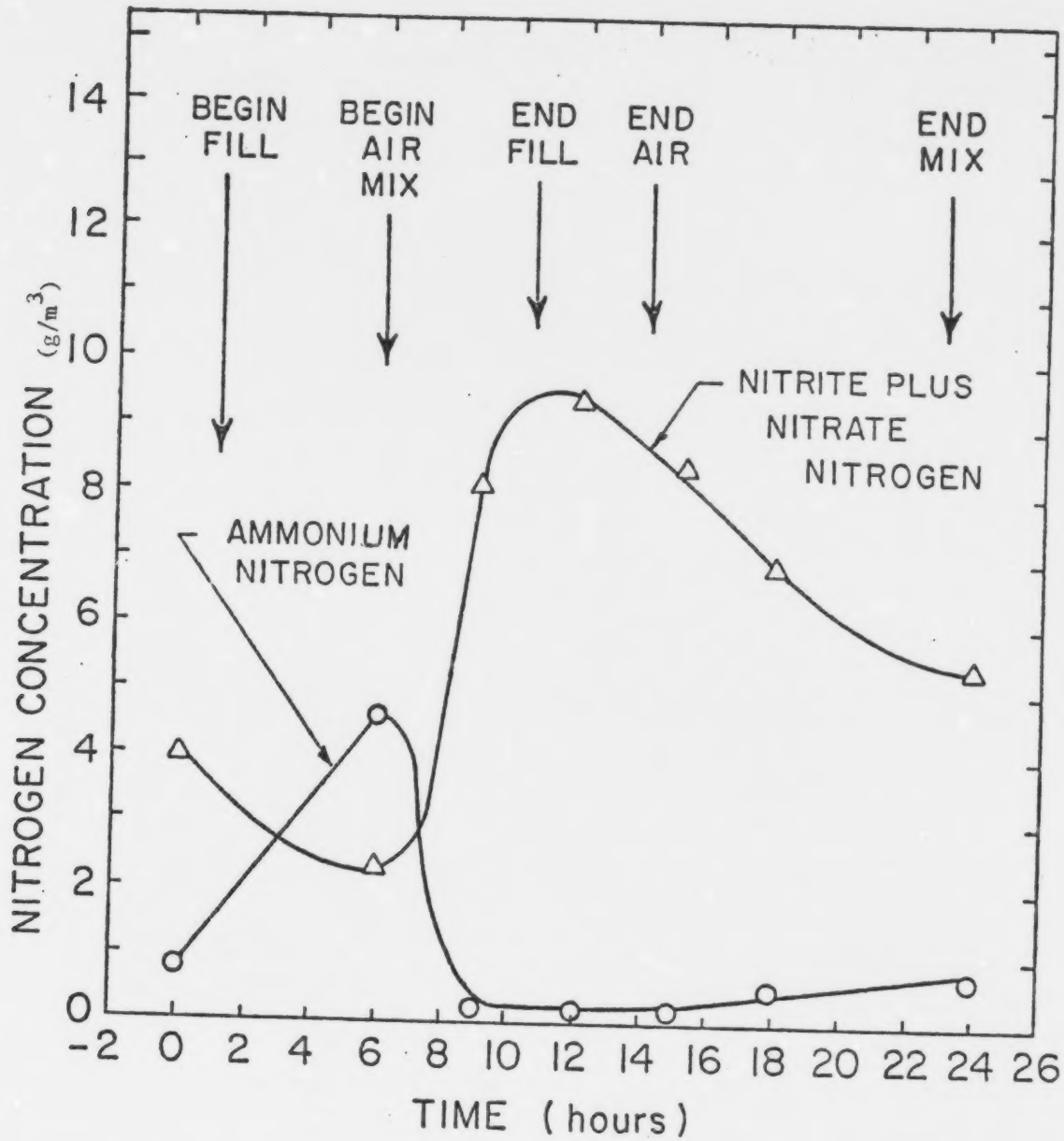
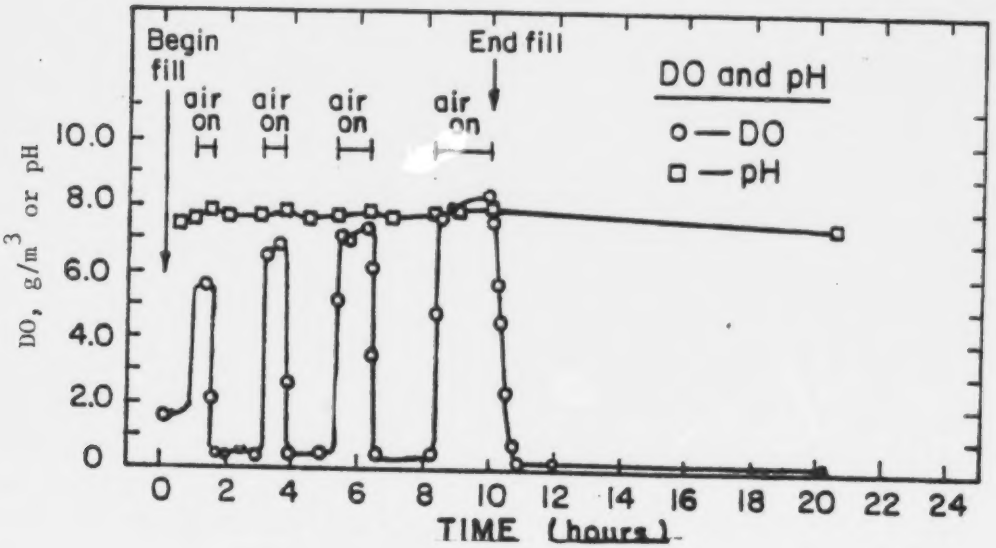


FIGURE 5. NITROGEN PROFILES FOR ONE COMPLETE CYCLE (2)

6.1



6.2

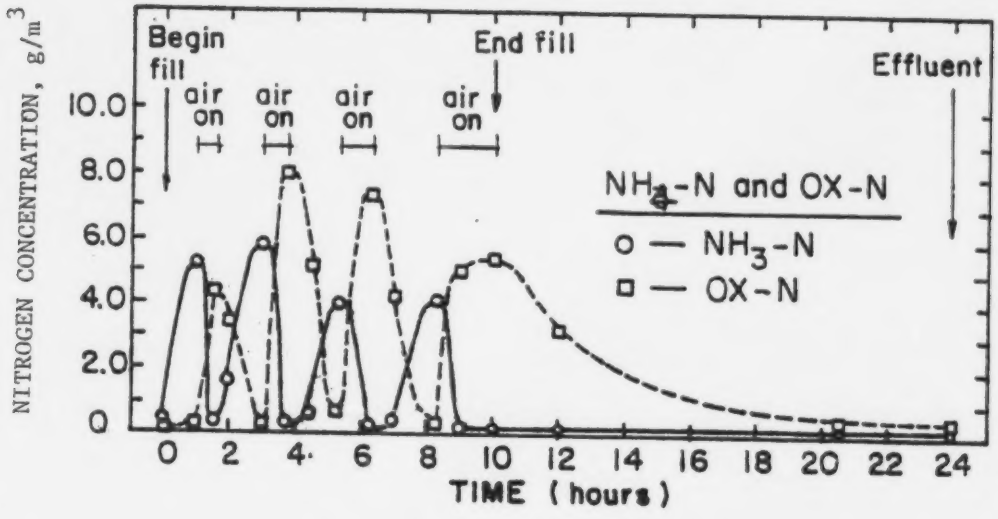


FIGURE 6. NITROGEN REMOVAL IN A LOW LOADED SINGLE TANK SBR (35)

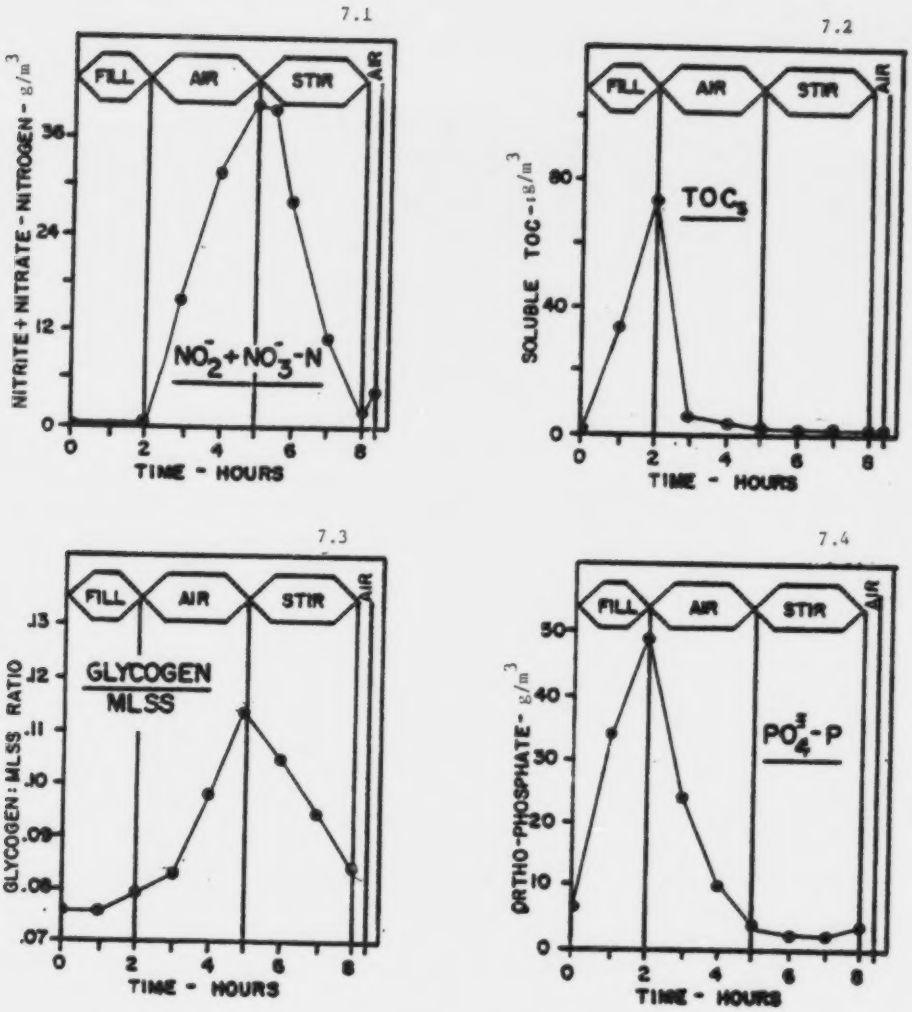


FIGURE 7. NUTRIENT REMOVAL DATA FOR TSB FED SBR (36)

essentially at background levels after the first hour into REACT, the additional five hours of REACT are necessary to form and them remove the glycogen. Without some portion of this extra time in REACT the organisms will likely develop poor settling characteristics. This was nicely demonstrated by Burke (6) in his pilot plant studies at Notre Dame between May 1977 and May 1978 where he showed the need for both elevated initial concentrations of substrate during FILL and sufficiently long periods of REACT in order to develop organisms with good settling characteristics.

FULL-SCALE FACILITIES

The retrofit plant in Culver, Indiana (1) served as the first full-scale demonstration plant for SBR treatment of domestic wastewater in the United States. At least four domestic waste plants are in various stages of design or construction. They are: Juneau, Alaska; Sabula, Iowa; LeClaire, Iowa; and Poolesville, Maryland. An SBR like facility started-up in July 1983 in Grundy Center, Iowa.

On the industrial side, Alphenrose Dairy owns and operates a two tank fill and draw system in Portland, Oregon. Single tank SBRs were reported to be used in Ada, Oklahoma for the treatment of cattle slaughter wastewaters and in Oklahoma City, Oklahoma for the treatment of wastewaters from a vehicle maintenance area for a utility company (2). Construction of a single tank SBR for a hazardous waste disposal site owned and operated by CECOS International, Niagara Falls, New York will begin in December, 1983 and Occidental Chemical Corporation has designed a similar system, with an early 1984 construction date, for the treatment of its landfill leachates in the Niagara Falls area.

A complete description of the Culver SBR experience is provided in the final report for that study (1). A brief summary of that report is repeated here so that a better understanding of SBR operation can be obtained.

A schematic for the Culver facility and general plant information are given in Figure 8 and Table 1 respectively. Typical preconversion operation involved use of either the comminuter or bar screens, followed in order by the grit chamber, two of the three primary clarifiers, one of the two aeration tanks, both secondary clarifiers and the chlorine contact chamber. Sludge was wasted to both aerobic digesters. The conversion was directed primarily at the two aeration tanks with the one closest to the control building identified as the North Tank (NT) and the other, the South Tank (ST).

After conversion, each tank was operated at a maximum liquid depth of approximately 3.4 m and, considering the Y-wall construction, was roughly 23 m long and 7 m wide. Major emphasis was placed on the following four areas:

- The Inlet and Inlet Chamber
- The Outlet
- The Aeration System
- The Control System

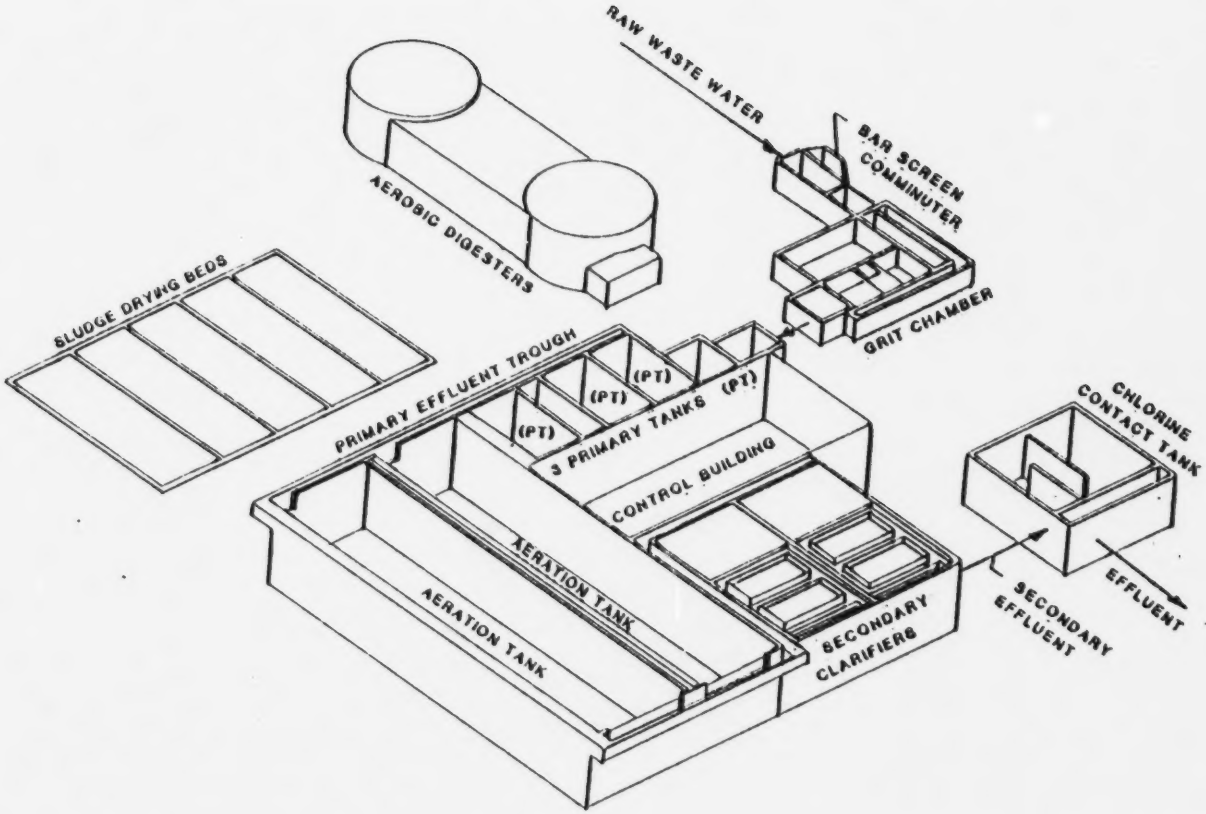


FIGURE 8. CULVER PLANT SCHEMATIC (1)

TABLE 1. GENERAL PLANT INFORMATION (1)

Yearly Average Flows:

1977: 1170 m^3/d

1978: 1120 m^3/d

1979; 1170 m^3/d

Tank Volumes:

Three Primary Clarifiers: 65 m^3 each

Two Aeration Tanks: 460 m^3 each

Two Secondary Clarifiers: 130 m^3 each

Chorine Contact Chamber: 65 m^3

Two Aerobic Digesters: 570 m^3 each

Approximate Loading:

0.2 kg BOD_5/kg MLSS-d

Type of Aeration

Two 45 kW Centrifugal Blowers

Course Bubble Diffusers

Capacity of Blower:

0.6 m^3/s

Each of the above areas is discussed briefly in the pages which follows. A general schematic of the aeration tanks showing modifications is provided in Figure 9 for convenience. A summary of manufacturers and suppliers for major equipment and materials used is presented in Table 2

The inlet and inlet chamber. An 8 inch (20 cm) pinch valve mounted to a stop gate replaced the inlet gate for each tank. Their operation was rather simple: a rubber bladder was inflated by a small air compressor (0.4 kW) at the end of FILL and air pressure released at the beginning of FILL. Two 3-way solenoid valves, controlled by a microprocessor, regulated air flow to one bladder or the other. A float switch signalled the microprocessor when the maximum liquid level was reached. Although the pinch valves worked quite well, the diameter selected limited flow through each valve to approximately 3000 m^3/d, and created unexpected problems during the late spring and summer of 1981, when record high flows reached the Culver plant.

The inlet chamber (see Figure 9) was formed by constructing a baffle wall of wooden planks perpendicular to the side walls some 2 m from the inlet. An open space of approximately 20 cm along the entire bottom of the wall allowed transfer of primary effluent to the main portion of the aeration tank. The inlet chambers minimized any short circuiting that might occur during FILL(1) operation.

The outlet. A float mounted submersible pump (7kW) direct coupled to suction draw-off pipe was installed in each tank (see South Tank, Figure 9). The draw-off pipe, parallel to the end wall, withdrew treated effluent approximately 36 cm below the water surface throughout DRAW. The beginning of DRAW was signalled (by the microprocessor) approximately 45 minutes after the beginning of SETTLE and continued for 40 to 45 minutes. The end of DRAW was determined by a float switch located approximately 1.4 m from the maximum water level. The microprocessor was also programmed to shut off the pump after a predetermined time (e.g. 50 minutes) in case the level switch malfunctioned. As a final precaution against the pump dipping into the sludge blanket and discharging mixed liquor to the stream, a support table about 1.2 m high was anchored to the tank floor beneath the decant device. The table served as a physical obstruction preventing further downward travel of the pump. The discharge from the pump passed through a jet disinfection unit (described below) before entering one of the two secondary clarifiers.

The decant device as installed served the general purpose of allowing SBR operation but had several basic design and operational problems:

- Decant took place too far below the water surface leaving behind a considerable volume of the treated effluent. A small modification brought the suction draw-off pipe closer to the surface but did not materially improve the situation.

- Pump maintenance was difficult. Although no pump maintenance problems were experienced during the course of the study, the

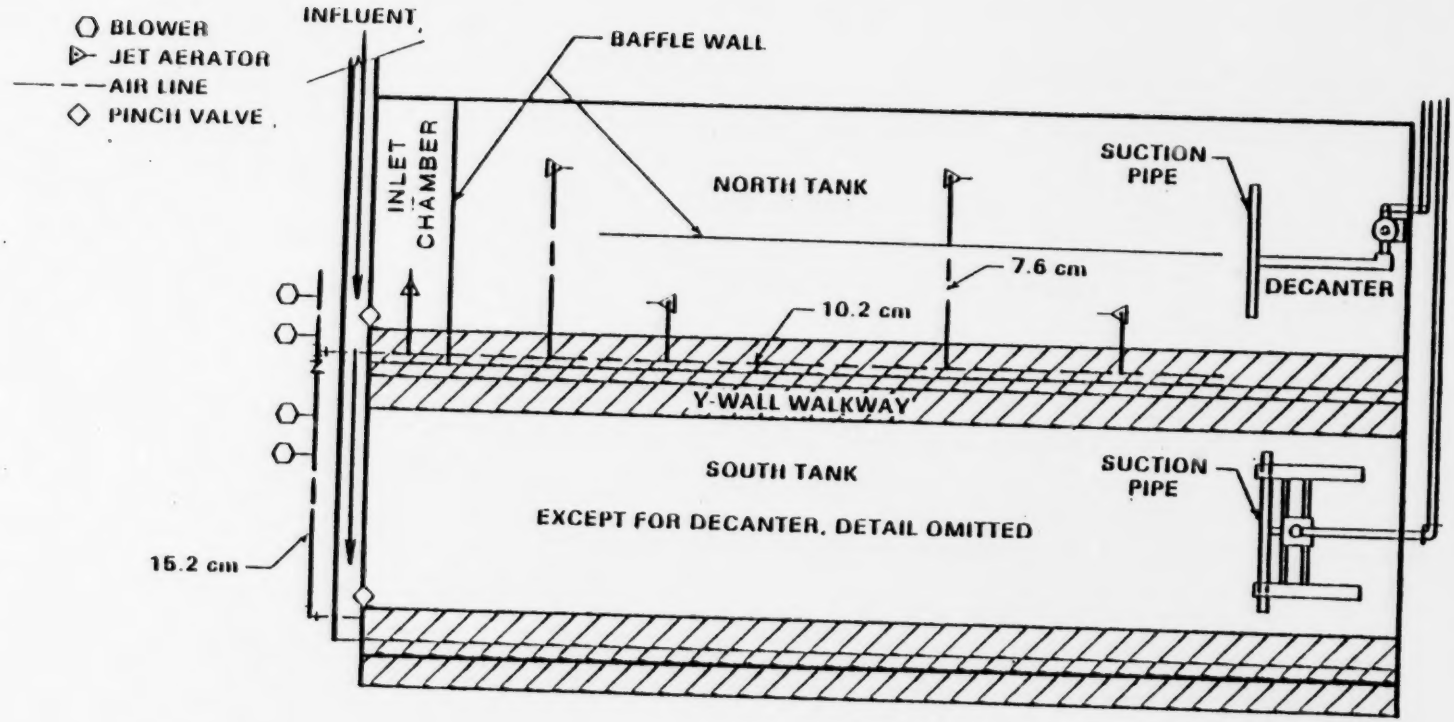


FIGURE 9. MODIFICATION OF AERATION TANKS AT CULVER (plan view) (1)

TABLE 2. SUMMARY OF EQUIPMENT AND MATERIALS USED (1)

Item	Use	Manufacturer/Supplier
Pinch Valves	Inlet Control	Red Valve Company
Stop Gates	Inlet Control	Sybron/Leopold, Inc.
Treated Lumber	Baffle Walls	Chicago Flame, Inc.
Misc. Structural Steel	Baffle Walls	Fabricated Steel Products
Float Switches	Level Control	Hydromatic Inc.
Aeration Blowers	Air Supply	Sunstrand Fluid Handling Inc.
Submersible Pumps	Mixing/Oxygen Transfer	Hydromatic Inc.
Fiberglass Pipe & Fittings	Air/Liquid Piping	Fibercast, Co.
Jet Aeration Nozzles	Oxygen Transfer	Pentech, Corp.
Submersible Pumps	Decant Pumping	Flygt Corp.
Pinch Valve	Decant Bypass	Red Valve Company
Jet Chlorination Unit	Disinfection	Pentech, Corp.
3 Way Solenoid Valve	Pneumatic Controls	Humphrey, Co.
Air Compressor	Pneumatic Controls	Ingersols Rand, Corp.
Microprocessor	Control	Xycom, Inc.
5 TI Controller	Sequencing of Unit Operations Automatically	Texas Instruments, Inc.

decant device was bulky and not easily reached and serviced. As a result, the system in the North Tank was changed in August 1980 by mounting the submersible pump on the end wall such that it could be easily lifted out for servicing (see North Tank, Figure 9). The suction draw-off pipe was connected to the pump through a swivel joint and floated below the surface by an air-filled, sealed ballast pipe.

- Because the suction pipe remained in the mixed liquor with open suction ports exposed during FILL, REACT and SETTLE, a small volume of mixed liquor accumulated in the pipe and around the support apparatus and was discharged, ultimately to the stream. After approximately 30 to 60 seconds into DRAW, the suction pipe and supports were clear of mixed liquor solids. Throughout the SBR study period, the average effluent SS from NT and ST after the initial flush of solids were 7 and 8 g/m^3 respectively. The average leaving the accumulated flow in the secondary clarifiers was 14 g/m^3. This difference between the SBR tanks and the final effluent amounts to only 1 kg of solids per flush. The decant device was modified at the end of the study period to return the first flush to the inlet chamber, thus solving this problem.

- Chlorination was accomplished using a jet disinfection unit. This unit is a coffin like box which aspirates chlorine through a jet pump located in the box whenever effluent from either tank is pumped through the box. The unit cannot quite handle the maximum potential flow rate from one decant pump (approximately 63 l/s). As a result, system flexibility was somewhat limited. For example, only one SBR tank could be discharged at a time and whenever the instantaneous flow rate to one tank increased severely, the time needed to discharge the other tank could not be shortened due to this discharge restriction.

In spite of the above difficulties the decant systems did perform quite satisfactorily throughout the study period even with the prototype construction.

The Aeration System. Five jet aerators (1.6 kW) were installed in each tank as is shown in Figure 9. Air lines fed each pump. Two high speed 7.5 kW aeration blowers were dedicated to NT and two to ST. A center baffle wall was installed (using the same materials as for the inlet chamber wall) to improve oxygen transfer. When the pumps were activated, the flow in the tank moved in a circular direction around the center baffle wall. Later in the study this center wall was removed from ST without any loss in performance.

Operation was generally rather simple. The pumping action of the jets was activated at the beginning of FILL(2) or at the end of FILL(1). When a float switch at approximately the 2.6 m level (from bottom) was tripped, the microprocessor activated the blowers to achieve aeration and FILL(3) was initiated. After the pinch valve closed, the blowers and jet aerators then remained on for REACT until one of two con-

ditions was satisfied: either the maximum allowable time in REACT was reached or the liquid level in the other tank tripped a switch, located at approximately the 2.5 m level, thus "informing" the microprocessor that SETTLE and DRAW must be initiated or the tank will not be ready for its turn at FILL.

Major problems were encountered with these high speed aeration blowers. Each installed blower failed and each replacement or modified unit either failed or developed the same mechanical whine that had preceeded failure of the earlier units. Because of the difficulties, only one blower was used at a time and then usually at 70% of capacity. As a result, the high D.O.'s needed for nitrification were not possible. The manufacturer finally resolved the difficulties but it was not until May 1981 that two blowers were operated in parallel so that the population of nitrifiers could be established.

Other than the difficulties with the blowers, the jet aeration system operated satisfactorily.

The Control System. The Electrical Engineering Department at the University of Notre Dame developed, built, and installed a microprocessor control system for the Culver facility. Unfortunately the control system developed many problems that could not be easily remedied by the treatment plant operator. The system finally failed completely in May 1981 and was replaced by a commercial unit which was installed in August 1981. The new system is quite easy to operate and adjust. Few additional problems are expected.

The microprocessor control system operated with either liquid level or time data. Level data were supplied by the float switches. Time was maintained by the microprocessor's internal clock. An example of one of the several control strategies implemented at Culver is summarized in Table 3.

The cost of the equipment and supplies used for the first round of modifications is summarized in Table 4. Of the $75,600 listed, $42,000 was used to replace totally the aeration equipment. In addition, the new commercial process controller system cost only $4000 (vs. the $12,000 for the unit fabricated at Notre Dame).

All data were obtained from daily grab samples collected on the raw wastewater (RWW), primary effluent (PE), north tank effluent (NT), south tank effluent (ST) and final effluent (FE). Tables 5, 6 and 7 provide rounded monthly average data for the SBR operating period (May 14, 1980 to May 23, 1981 and August 19, 1982 to December 31, 1981). Note that phosphorus was removed chemically by adding either alum or ferric chloride.

Because of both aberrant high rainfall and raw wastewater flow rates (see Table 8) and the final breakdown of the University fabricated microprocessor, the Culver facility operated in a modified continuous flow mode between May 24, 1981 and August 18, 1981, with the final clarifiers in usual operation with recycle pumps. Each morning between approximately 6:30

TABLE 3. CONTROL OF SBR AS VIEWED FROM NORTH TANK SWITCHES (1)

Float Switch Level NT (meters above bottom)	Function	Override Time Control For Function Listed
2.0 (ST in FILL)	• End DRAW NT • Begin IDLE NT	• Maximum Time in DRAW = 50 minutes
2.0 (NT in FILL (1))	• End FILL(1) NT • Begin FILL (2) NT	• None
2.5	• End REACT ST • Begin Settle ST	• Maximum Time in REACT = 90 minutes • Time St in SETTLE = 45 minutes
2.6	• End FILL (2) NT • Begin FILL (3) NT	• None
3.4 (ST in IDLE)	• End FILL (3) NT • Begin REACT NT • End IDLE ST • Begin FILL (2) NT	• None
3.4 (ST in DRAW)	• End FILL (3) NT • Begin REACT NT • End DRAW ST • Begin FILL (1) ST	• None

Notes:

- FILL (1) is the simultaneous filling and discharge of the tank.
- FILL (2) is filling with mixing only (i.e. blowers not on) and no discharge.
- FILL (3) is filling with mixing and aeration and no discharge.

TABLE 4. SUMMARY OF MODIFICATIONS AND APPROXIMATE COSTS FOR CULVER, INDIANA, RETROFIT, 1340 m^3/d (1)

Item	Description	Approx. Cost
Pinch Valves (2)	Regulate Inlet Flow	$3,500
Stilling Chamber Lumber	Allow FILL (1)	1,300
Center Wall Lumber	Improve Oxygen Transfer	3,000
Compressors	Four at 7.5 kW each	6,000
Directional Jets	Five per Tank at 1.6 kW each	23,000
Air Lines and Valves	Air Supply to Jets	9,500
Decant System (2)	Floating Submersible Pump	15,000
Decanter Platforms (2)	Limit Decanter Discharge	500
Level Detectors (8)	Monitor Liquid Level	3,300
Motor Control Center (1)	Control Installed Equipment	6,000
Microprocessor	Control System	4,000
	Total	$75,600

TABLE 5. AVERAGE MONTHLY DATA (ROUNDED) FOR 5-DAY BOD AND SUSPENDED SOLIDS FOR SBR OPERATION PERIOD (1)

DATE		BOD_5, g/m^3					SUSPENDED SOLIDS, g/m^3				
		RWW	PE	NT	ST	FE	RWW	PE	NT	ST	FE
1980	MAY	160	120	6	9	2	120	80	7	10	11
	JUN	140	100	6	6	3	120	80	5	4	9
	JUL	180	120	11	8	4	140	80	7	6	8
	AUG	130	100	10	14	11	100	70	5	9	12
	SEP	140	120	11	14	5	120	90	8	7	14
	OCT	170	130	10	9	4	170	80	10	9	12
	NOV	180	150	9	8	3	150	70	6	8	13
	DEC	160	110	10	11	6	120	70	7	9	14
1981	JAN	160	130	9	10	3	120	80	10	10	15
	FEB	160	150	13	16	7	120	70	9	13	24
	MAR	170	130	8	9	5	140	80	7	9	17
	APR	170	100	8	9	12	160	70	8	15	23
	MAY	130	90	8	8	7	110	70	6	9	17
	AUG	110	90	5	7	4	120	70	3	5	9
	SEP	170	100	6	5	3	170	70	3	3	7
	OCT	160	110	11	10	4	160	80	4	6	12
	NOV	170	130	14	10	8	170	100	10	6	9
	DEC	180	120	12	13	11	130	90	6	8	12
	AVG	160	120	10	10	4	140	80	7	8	14
	DATA PTS	211	210	204	203	202	357	356	352	252	251

RWW = Raw Wastewater PE = Primary Effluent FE = Final Effluent
ST = South Tank NT = North Tank

TABLE 6. AVERAGE MONTHLY DATA (ROUNDED) FOR NUTRIENTS FOR SBR OPERATING PERIOD (1)

DATE	NH_4-N g/m^3 as N					NO_x-N g/m^3 as N					PHOSPHORUS* g/m^3 as P				
	RWW	PE	NT	ST	FE	RWW	PE	NT	ST	FE	RWW	PE	NT	ST	FE
MAY	22	20	19	18	19	7	7	0.6	0.7	1.4	6	6	1.0	1.1	0.9
JUN	16	15	15	14	15	6	5	0.8	1.4	1.2	5	5	0.4	0.4	0.6
JUL	23	21	18	17	19	8	7	7	5	5	7	7	0.3	0.3	0.6
AUG	18	16	17	10	9	8	7	7	5	5	6	7	0.3	0.4	0.7
SEP	20	19	5	8	6	8	7	6	4	5	6	6	0.5	0.3	0.7
OCT	23	22	15	19	18	8	8	2.5	0.8	1.5	9	8	0.4	0.6	1
NOV	21	23	20	21	21	8	7	0.7	1.0	1.4	8	7	0.3	0.4	0.7
DEC	19	19	17	17	18	4	3	0.5	0.5	0.7	7	6	0.6	0.6	0.9
JAN	22	21	19	19	20	5	5	0.6	0.5	0.7	6	5	0.5	0.4	0.7
FEB	17	17	16	16	17	2.5	2.5	0.4	0.6	0.5	5	4	0.5	0.6	0.9
MAR	20	19	19	18	18	2.8	2.6	0.4	0.4	0.4	6	5	0.4	0.4	0.7
APR	17	17	17	16	16	2.4	2.3	0.4	0.5	0.3	5	4	0.6	0.6	0.8
MAY	17	16	13	13	13	1.4	1.6	0.4	0.4	0.4	5	5	0.9	0.9	1.1
AUG	16	13	0.3	0.8	0.6	1.9	1.8	1.7	1.2	1.6	5	4	0.9	0.9	0.9
SEP	20	17	0.8	0.7	1.0	1.9	2.2	1.6	1.6	1.7	7	6	0.8	1.0	1.0
OCT	19	19	1.4	0.6	1.8	2.2	2.2	1.0	1.1	1.0	6	5	0.6	0.7	0.8
NOV	23	20	1.7	0.7	1.0	2.6	1.8	1.2	1.4	1.2	7	5	0.7	0.7	0.7
DEC	20	18	0.9	1.9	1.3	1.6	1.8	1.2	1.4	1.4	8	6	0.6	0.9	0.8
AVG	19	18	11	11	12	5	4	1.6	1.4	1.5	6	4	0.5	0.6	0.8
DATA PTS	290	288	285	284	289	290	289	287	286	286	305	303	303	302	305

RWW = Raw Wastewater PE = Primary Effluent FE = Final Effluent
ST = South Tank NT = North Tank

* Effluent P values reflect addition of ferric chloride or alum.

TABLE 7. AVERAGE MONTHLY DATA FOR REACTOR SOLIDS, SLUDGE VOLUME INDEX, FLOW AND PRECIPITATION FOR SBR OPERATING PERIOD (1)

DATE		MLSS, g/m^3		SVI ml/g		FLOW, m^3/d	PPT, mm
		NT	ST	NT	ST		
1980	MAY	1700	1700	150	140	1240	86
	JUN	2300	1900	130	130	1250	113
	JUL	2500	1900	110	100	1240	60
	AUG	2800	2300	120	100	1350	208
	SEP	2800	2400	120	130	1340	103
	OCT	2600	2100	180	150	1230	79
	NOV	2400	2100	200	140	1170	50
	DEC	2400	2400	150	140	1300	102
1981	JAN	2100	2300	130	110	1320	8
	FEB	2400	2300	140	100	1470	66
	MAR	2400	2000	130	100	1260	38
	APR	2200	2000	190	120	1600	212
	MAY	2700	2400	140	110	1980	215
	AUG	2700	2300	110	140	1570	66
	SEP	2800	2300	190	130	1330	108
	OCT	2700	3000	190	130	1430	71
	NOV	2800	2400	140	110	1250	128
	DEC	3100	2400	130	90	1160	51
	AVG	2500	2200	150	120	1340	-
	DATA PTS	403	400	392	392	508	-

ST = South Tank NT = North Tank

TABLE 8. MONTHLY AVERAGE DATA (ROUNDED) FOR THE MODIFIED CONTINUOUS FLOW OPERATING PERIOD (May 24 to Aug. 18, 1981) (1)

	PPT	FLOW	BOD_5, g/m^3			SS, g/m^3			NH_4-N, g/m^3			NO_x-N, g/m^3
	mm	m^3/d	RWW	PE	FE*	RWW	PE	FE	RWW	PE	FE	FE
MAY	44	1740	110	40	14	90	40	9	15	14	12	1.0
JUN	432	2370	110	70	9	130	50	9	9	9	4	1.1
JUL	131	2030	130	70	6	160	60	6	15	12	0.8	2.1
AUG	17	1510	130	80	5	140	70	7	18	15	1.0	1.8
AVG	-	2010	120	70	8	140	60	8	13	11	3	1.6**
NO.+	-	88	28	28	28	57	57	57	37	37	37	34

* Post-chlorination

** Average Raw Wastewater NO_x-N concentration was also 1.6 g/m^3

+ Total number of observatons for all months

RWW = Raw Wastewater PE = Primary Effluent FE = Final Effluent

AM and 10:00 AM the jet aeration mixing pumps and blowers were shut off so that sludge accumulated in the secondary clarifiers could be pumped-down and returned to the reactor. During this time, the clarified supernatant in the aeration tanks was "pushed" into and through the clarifiers by the primary effluent entering the tanks. By 10:00 AM power to the aerators was restored and the system was operated as a conventional continuous flow facility (i.e., in the same manner used prior to SBR conversion). This modified continuous flow mode has some characteristics of many of the periodic systems operated in Denmark.

During modified continuous flow operation, both aeration tanks were used in parallel in May and June. Only the South Tank was used in July and only the North Tank in August. Plant performance during this period was also quite good as shown by from the data presented in Table 8. As can be seen from the data, nitrification and denitrification began in June 1981. Excellent biological nitrogen removal continued during SBR operation between August and December 1981 as indicated in Table 6.

SECTION 3

TECHNOLOGY EVALUATION

PROCESS THEORY

Population Dynamics

In every cycle of the SBR, microorganism selection pressures are quite severe. During the initial portion of FILL the microorganisms are subjected to anaerobic (zero D.O. and no measureable concentrations of oxidized nitrogen to serve as an electron acceptor) and/or anoxic (zero D.O. but with oxidized nitrogen present) conditions. During this time unreacted and partially reacted substrates (e.g. organics and ammonium nitrogen) accumulate in the reactor. When the air is finally added to the reactor, either during FILL or at the beginning of REACT, the microorganisms which survive utilize the accumulated substrates at a high rate. The rapid rate of substrate utilization encourages two basic reaction schemes to develop. One involves the manufacture of high levels of certain intracellular components. The other revolves around the production of shunt or by-products which ultimately serve as a food source for other microorganisms in the mixed culture environment. Towards the end of REACT starvation conditions resulting from the absence of extracellular substrate dominate the systems. As a result, in every cycle of the SBR, the mixed culture of microorganisms are subjected to feast and famine as well as high and essentially zero D.O. conditions. Only a limited number of microorganisms can both survive and compete in this environment.

Because of the severe selective pressures imposed, population dynamics for a given type of wastewater (e.g. a domestic waste) is under the direct control of the treatment plant operator. In a conventional continuous flow activated sludge facility, population dynamics is largely influenced by the unsteady state nature of the influent wastewater. By way of contrast, the unsteady state nature of the SBR operation overwhelms variations in the wastewater, thus resulting in a more controllable system.

As far as population selection is concerned, the operator can easily either relax or eliminate some of the selective pressures. For example, anoxic conditions can be extended or eliminated and, as a result, the maximum rate of substrate utilization relative to the average rate can be altered. Obviously this would change the organism distribution in the mixed culture and, depending upon the operating strategy selected, allow variations in

the influent wastewater to become more or less important. Figures 10 and 11 summarize how different aeration control strategies can influence the concentration of substrate in an SBR. Since the rate of organisms growth depends directly on the concentration of substrate, the different aeration strategies directly affect the rate of growth.

While the organism selection potential of the SBR and the operators command over the selection process are clear, it is not obvious that the organisms thus selected are those that would be beneficial to the proper operation of an activated sludge type system. In this regard, two major observations have been made. The first is that the RNA content of the microorganisms selected in the SBR is much greater than what would be expected from a conventional continuous flow system (39). The growth rate of microorganisms has been directly linked to the RNA content of the cells. This evidently provides the microorganisms selected with the advantage they need to compete because elevated levels of that intracellular machinery necessary to utilize the extracellular substrate immediately are available as soon as the aeration system is activated. Thus for each unit mass of MLSS present in the SBR, more microorganisms are capable of processing a greater quantity of substrate at a rate greater than is possible in a conventional continuous flow system. This must be considered a beneficial "side-effect."

The second major observation was recently reported by Chiesa and Irvine (40). Chiesa first showed that the sludge volume index (SVI) of an SBR culture was independent of sludge age and mass loading and directly related to the fraction of time a two hour FILL period was aerated in each of six SBR systems. As can be seen from Table 9, the SBR labeled A was unmixed throughout FILL and that labeled F was aerated throughout FILL with reactors B through E subjected to intermediate aeration strategies. As the fraction of aeration increased, the maximum substrate concentration decreased and the SVI increased. The higher SVI's were always associated with increased numbers of filaments. These findings and others (40) led Chiesa to postulate a hypothesis for control of filaments in the SBR. This hypothesis is summarized in Figure 12. Simply stated this figure allows for two general types of filaments, one which will dominate at low substrate concentrations (less than S*) and one at high substrate concentrations. Those filaments that grow well at low substrate concentrations have low growth rates at high substrate levels. Those that grow well at high concentrations have very high death rates (negative net growth rates) during starvation conditions. The floc forming zoogleal organisms compete well at both high and low substrate levels. As a result, the alternating high and low substrate concentrations in an SBR limits the growth of either filament type while allowing normal growth of floc forming organism. Clearly any operating strategy which minimizes the impact of filamentous organisms must also be considered a beneficial "side-effect."

The above discussion is not meant to be limited exclusively to the SBR. Continuous flow activated sludge systems that simulate plug flow environments (e.g. tanks-in-series) also subject organisms to alternating conditions of high and low growth rates in a space rather than a time oriented configuration. An interesting point of comparison here, however, is that the time devoted to anoxic or aerobic conditions is easily adjusted in an

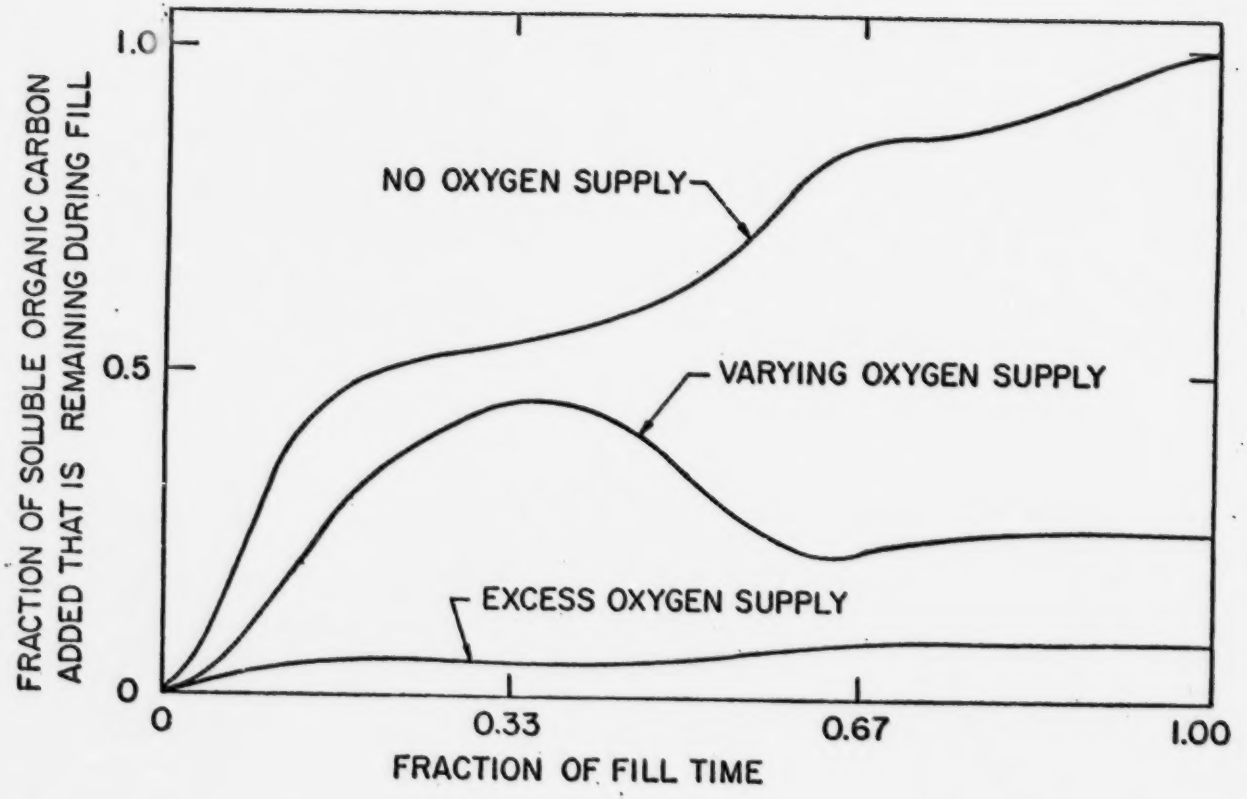


FIGURE 10. SOLUBLE ORGANIC CARBON REMAINING AS A FUNCTION OF FILL TIME FOR DIFFERENT OXYGEN SUPPLY RATES (HYPOTHETICAL) (31)

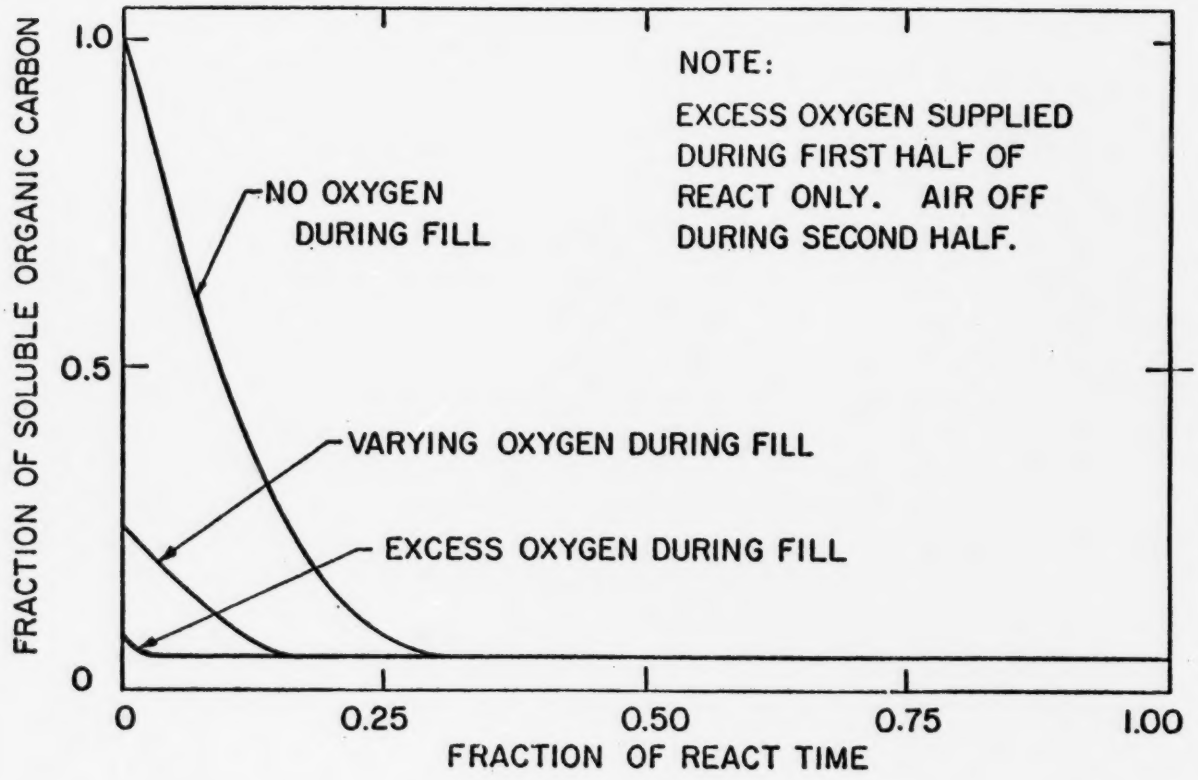


FIGURE 11. SOLUBLE ORGANIC CARBON REMOVED DURING REACT WITH INITIAL CONCENTRATION SET BY DIFFERENT OXYGEN SUPPLY RATES (31) DURING FILL (HYPOTHETICAL)

TABLE 9. MIXED LIQUOR SETTLING PROPERTIES (40)

REACTOR CONTROL STRATEGY	PERCENT AERATED FILL TIME	MAXIMUM REACTOR SUBSTRATE CONCENTRATION (mg TOC l^{-1})	SVI (ml g $MLSS^{-1}$)
A	0.0	91 (95)[a]	52-58
B	12.5	87 (91)	58-65
C	25.0	82 (87)	80-90
D	37.5	77 (81)	110-120
E	50.0	63 (70)	>600
F	100.0	13 (-)	>600

[a] First number was measured experimentally, number in parentheses represents the theoretical value, including background, at the start of aeration assuming no reactions during fill.

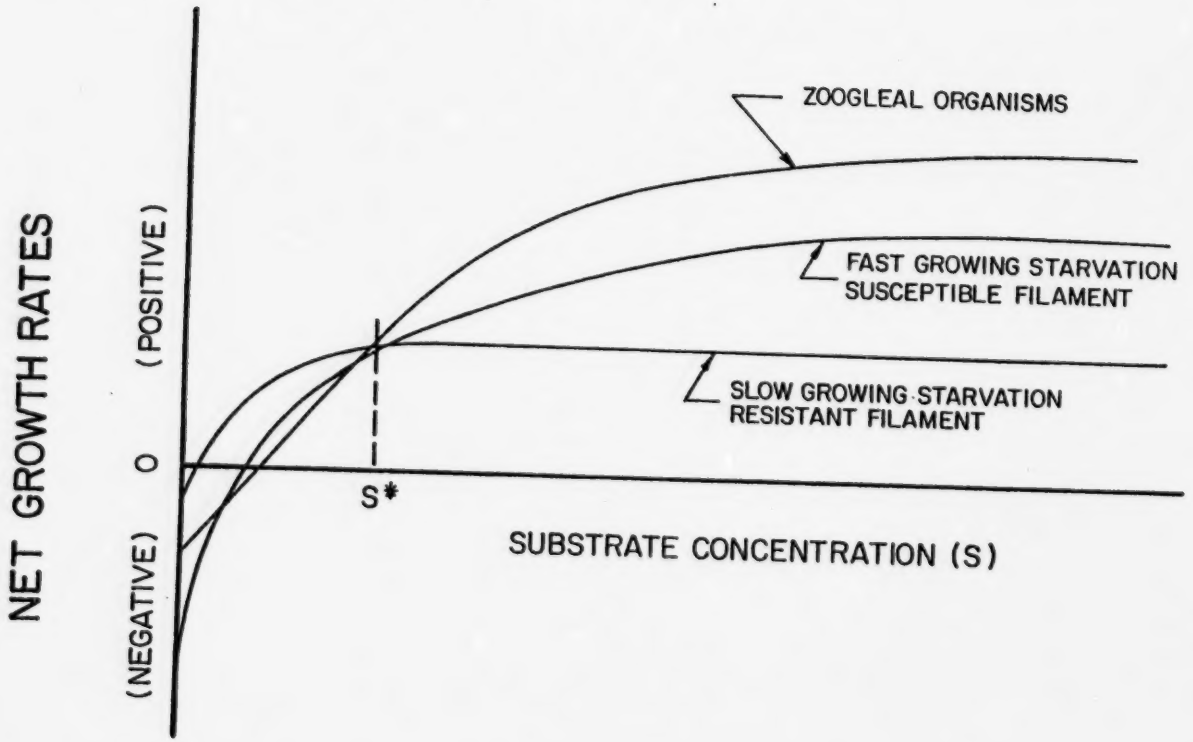


FIGURE 12. MICROBIAL GROWTH AND COMPETITION INCLUDING STARVATION INDUCED DEATH (40)

SBR where the spacial adjustments of such conditions in a continuous flow system is not readily attainable.

Oxygen Supply

Because of the tremendous impact that oxygen supply has on the rate of organism growth and the resulting selective pressures, careful attention must be given to this aspect of SBR operation. A simple rule to follow is that sufficient oxygen and time must be supplied during REACT to allow the rate of D.O. climb to increase abruptly at least once each day in each tank. A more restrictive and conservative constraint would be to require this condition once each cycle. By doing this, all extracellular and readily degradable intracellular substrates will be reduced to background levels. This constraint is, of course, easily met during early morning hours at most domestic wastewater treatment facilities. Another guideline is that the D.O. does not have to exceed 0.5 g/m^3 during FILL or most of REACT, provided that the D.O. reaches approximately 2 g/m^3 at least once each day in each tank. While the appropriate operating procedure would have to be determined in the field on a case by case basis, these two rules can be used directly to size the aeration equipment.

Because the D.O. during FILL can be less than 0.5 g/m^3, oxygen transfer takes place with the maximum driving force during this period and balances the fact that oxygen transfer is less efficient at the shallower tank depths. The cumulative process oxygen transferred each day, however, must be equal to the net (in minus out) chemical oxygen demand (COD) supplied by the wastewater minus the COD of the sludge wasted each day. These principles are discussed in more detail in the latter part of this section.

Equalization

Each tank in an SBR will receive wastewater input from roughly two to twelve hours each cycle. Depending upon the mixing and aeration policy, the time in FILL is equivalent to having separate facilities for step-wise equalization. In addition the liquid in the tank at the beginning of FILL provides a buffer against rapid changes in the concentration of any component in the reactor that could result because of sudden increases in strength of the influent wastewater.

Solids Separation

All energy from mixing and/or aeration during REACT must be dissipated before proper sedimentation can begin. This is readily accomplished in a basin in about five to ten minutes. This brief period of turbulence at the beginning of SETTLE seems to assist in flocculation necessary for final sedimentation.

The time actually set aside for SETTLE includes virtually all the time in DRAW for a surface withdrawal device. With such a device the effluent decanted is always the highest quality available in the tank at any time. A fixed mounted withdrawal system must wait for the sludge to settle past the point of discharge before DRAW can begin.

Because the SVI of the mixed liquor is under the control of the operator, solids separation is not a problem in the SBR. Because nitrification oriented systems tend to develop a surface scum and because of the obvious problem of other miscellaneous floating material in any sedimentation tank, the withdrawal device should be either just beneath the surface or, if directly on the surface, protected by a boom like arrangement which prevents floatables from entering the discharge.

PROCESS CAPABILITIES AND LIMITATIONS

Process Capabilities

Except as described under limitations, bench-scale SBR systems consistently produced effluent BOD_5 and SS of less than 20 g/m^3, and usually less than 10 g/m^3, each (2,25,26,28,30,35,37,38,39). In addition, these systems typically produced effluent ammonium nitrogen levels of less than 1 g/m^3 whenever nitrification oriented aeration strategies were employed and oxidized nitrogen, less than 2 g/m^3 in systems where denitrification mixing and aeration strategies were used. Because the Culver demonstration study (1) systematically addressed the question of BOD_5 and SS removal first and then investigated biological nitrogen removal, performance at Culver for the removal of BOD_5, nitrogen and the chemical removal of phosphorus is summarized below.

Between May 1980 and May 1981, the Culver SBR produced average BOD_5 and SS concentrations of less than 10 g/m^3 each as is shown below.

	Raw Wastewater	Effluent NT	Effluent ST
BOD_5, g/m^3	160 (152)*	9 (147)	10 (144)
SS, g/m^3	130 (153)	7 (258)	9 (258)

*( ) = number of observations

Effluent BOD_5 measurements were conducted on pre-chlorination samples. Post chlorination BOD_5 effluent averaged 5 g/m^3 (143 observations).

Nitrification requires that the D.O. be greater than approximately 0.5 g/m^3. The initial mixing (no aeration) period of FILL is clearly in conflict with this need. As a result, the aeration time during FILL and REACT must be sufficiently long and the D.O. must be sufficiently high to allow both the enrichment of nitrifiers in the system and the completion of ammonium-nitrogen (NH_4-N) oxidation. At Culver, problems with the aeration equipment prevented the D.O. from climbing above 0.5 g/m^3 during virtually all of FILL and sometimes part of REACT. While the BOD_5 and SS removals were not affected by the low D.O.'s , nitrification was not possible until June 1981, when the aeration equipment was repaired and higher D.O. could be maintained. Average NH_4-N data (and SS and BOD_5 for comparison) for pre-and post-nitrification periods is summarized below:

	Raw Wastewater	Effluent NT	Effluent ST
May '80 to May '81:			
NH_4-N, g/m^3	19 (208)*	15 (206)	15 (206)
Aug. '81 to Dec. '81:			
NH_4-N, g/m^3	20 (82)	1.1 (79)	1.0 (78)
SS, g/m^3	150 (94)	5 (94)	6 (94)
BOD_5, g/m^3	170 (59)	11 (57)	10 (59)

Post-chlorination BOD_5 effluent (Aug. '81 to Dec. '81) = 7 g/m^3

*( ) number of observations

Denitrification requires the D.O. to be less than approximately 0.5 g/m^3, the presence of nitrite and/or nitrate nitrogen (the sum of these two is reported as NO_x-N) and a carbon source for energy. The mixing-only period of FILL (i.e. FILL(2)) provides the best conditions for denitrification until the oxidized nitrogen supply, left in the residual liquid after DRAW, is exhausted. After all available NO_x-N is depleted, anaerobic reactions take place. The aeration portion of FILL (i.e. FILL(3)) is compatible with denitrifiction in that NO_x-N will be produced provided the D.O. is high enough but incompatible in the sense that the electron donor, in this case organic carbon, entering with the primary effluent is being oxidized aerobically with oxygen as a terminal electron acceptor, rather than anoxically with NO_x-N as the terminal electron acceptor. On the other hand the D.O. during this period of FILL and REACT must be high enough and maintained long enough to allow the oxidation of the entering ammonim-nitrogen, but low enough and of sufficient duration to allow denitrification. This can be accomplished by providing both aerobic and anoxic conditions in a time sequence.

All of the above process considerations for denitrification can be engineered into a new facility. At Culver, BOD_5 and SS removal and ammonium oxidation were considered quite likely even under the constraints of a retrofit. This was borne out by the data presented above for the period August 1981 to December 1981. Bench-scale studies suggested, however, that denitrification (except for the expected removal of the surprisingly high input of NO_x-N in the raw wastewater) would be difficult to achieve. As is shown below, these concerns were unfounded.

	Raw Wastewater	Effluent NT	Effluent ST
May '80 to May '81:			
NO_x-N, g/m^3	5.4 (210)*	1.7 (107)	1.4 (205)
NH_4-N plus NO_x-N, g/m^3	24**	17	16
Aug. '81 to Dec. '81:			
NO_x-N, g/m^3	2.0 (80)	1.3 (81)	1.3 (81)
NH_4-N plus NO_x-N, g/m^3	22	2.4	2.3

*( ) = number of observations

** = sum of averages of NH_4-N and NO_x-N

The ammonium plus oxidized nitrogen data represent an estimate of the input nitrogen that was available for denitrification. The actual amount could be either more or less depending upon the amount of organic nitrogen that was processed into ammonium-nitrogen or cell mass. From random samples collected, the concentration of organic nitrogen in the raw wastewater was found to be between 10 and 15 g/m^3 and between 1 and 3 g/m^3 in the effluent (as N).

While BOD_5, SS, ammonium and oxidized nitrogen reductions were achieved biologically, phosphorus removal at Culver was accomplished by adding ferric chloride (until October 24, 1981) or alum (after October 24, 1981). While the Town of Culver is required to meet a 1 g/m^3 effluent limitation of phosphorus, biological phosphorus removal was not attempted at Culver. This is not meant to suggest that biological phosphorus removal is not possible in an SBR. In fact, recent bench-scale studies have shown that biological phosphorus removal is easily achievable in the SBR (39). Nevertheless, biological phosphorus removal at Culver is probably not possible because of the unexplained high concentrations of oxidized nitrogen in the raw wastewater which prevent the strict anaerobic conditions necessary for biological phosphorus removal.

Chemical phosphorus removal at Culver was achieved rather simply. Either a ferric chloride or alum solution was added continuously at a constant rate (9 kg/d ferrous ion or 42 liters/d of 8.1% Al_2O_3) to the primary effluent. The results of this effort are summarized below for the two discrete periods discussed previously.

	Phosphorus, g/m^3-P		
		Effluent	
	Raw Wastewater	NT	ST
May '80 to May '81	6.3 (221)*	0.4 (218)	0.5 (217)
Aug. '81 to Dec. '81	6.5 (84)	0.7 (85)	0.8 (85)

*( ) = number of observations

The effluent phosphorus concentrations listed for August 1981 to December 1981 were generally higher during each month of this period independent of the chemical used for precipitation and were probably due to the lower pH observed (about 0.5 to 1 pH units) resulting from nitrification which occurred during this period.

An unusual but real capability of the SBR is that the aeration strategy can be easily adjusted so that nitrification will not take place. Such an objective is not readily achievable in conventional continuous flow facilities where unwanted nitrification during the summer months can result in excess energy demands and oxygen limited conditions.

While the discussion herein is directed primarily at the treatment of municipal wastewaters, the SBR has been used to treat industrial wastewaters as well. Chiesa and Irvine (41)addressed this application at a 1982 American Institute of Chemical Engineers meeting in Cleveland. A detailed discussion of the use of SBRs in the treatment of leachates from industrial landfills is also available (42).

Process Limitations

Two major limitations became apparent during the developmental stages of the SBR. The first was that it is a non-continuous flow system that had no real operating counterpart in the United States. This was a significant liability which, as a result of the successfully operated U.S.E.P.A. demonstration study at Culver (1), has been largely, but not entirely, overcome. The second major limitation was the perception that the SBR had value in only small systems. At first a flow limitation of approximately 380 m^3/d was suggested strongly (3). Later a limit of 3785 m^3/d was stated (4). For purposes of the cost analyses present in this assessment, a limit of 18,925 m^3/d was considered reasonable. The author's opinion is that there is no theoretical or technical reasons for any upper limit, and that system selection should be based on a cost-effectiveness analysis for each specific application and the level of reliability and consistency desired. Nevertheless engineers wishing to implement SBR technology should be aware of the potential difficulties in gaining acceptance of such a system.

More real (rather than perceived) limitations include the freezing of scum (if present) during winter operating conditions, high effluent SS for high mass loaded systems, the need to produce an effluent with a low con-

centration of soluble organics and, finally, the possibility of developing an organism population which has a large number of filaments. Each of these is discussed separately below.

As was noted earlier, scum was present on each reactor at Culver throughout most of the study period. Since decant was from below the surface, operating difficulties did not occur unless extreme winter conditions developed. In this case, the scum would freeze and the float switches would lift vertically without tipping. The frozen scum, if thick enough, would also hamper the operation of the decanter in the North Tank. The decanter in the South Tank was sufficiently massive to overcome any icing difficulties. This problem could have been eliminated at Culver if skimming devices had been installed. Without the scum, any ice that would have formed during SETTLE and DRAW could have been broken-up with mixing (and possibly aeration) during IDLE during extremely severe temperature conditions. Alternatively, a cover over the tanks in more northern climates might serve as a useful solution. More recent studies at Culver have shown that the aeration strategy associated with nitrification is somehow linked to scum production. As a result, nitrification was eliminated in one of the two tanks and the scum level in that tank was markedly reduced.

The mass loading at Culver and most of the bench-scale systems (on a unit mixed liquor volatile suspended solids (MLVSS) basis) was usually less than 0.4 kg BOD_5/kg MLVSS-d. Effluent SS from these reactors was generally less than 10 g/m^3. Mass loadings of one to two kg of soluble BOD_5/kg MLVSS-d have, however, been investigated in the laboratory. Almost without exception these reactors produced an effluent SS greater than 30 to 40 g/m^3 which was evidently due to dispersed growth that did not adhere to the settling mixed liquor solids. The soluble BOD_5 from these systems was always less than 10 g/m^3. An interesting note here is that these high loadings have not been investigated in the SBR for municipal wastewaters. For such systems the soluble BOD_5 content of the influent wastewater is typically 20 to 50 percent of the total BOD_5. As a result, an SBR with a mass loading between one and two kg total BOD_5/kg MLVSS-d may not produce as large a concentration of dispersed growth and may be able to achieve consistently an effluent SS of less than 30 g/m^3.

Aeration and mixing strategies can be selected which both limit the growth of filaments and enhance them. Two aeration and mixing strategies increase the likelihood of filaments. One is aeration throughout FILL and REACT. This readily develops filaments for a feed which is totally soluble and easily degradable in SBRs loaded at less than approximately 0.5 kg BOD_5/kg MLVSS-d. The full impact of a totally aerated FILL and REACT for insoluble substrates (such as in domestic wastewater) and difficult to degrade organics is not clear and must be studied further. Low mass loadings (less than approximately 0.05) in SBRs fed domestic wastewater have not, however, developed filaments to the extent that settling is impaired.

The second aeration and mixing strategy which increases filament production is one in which insufficient time is provided during REACT to oxidize fully the extracellular and readily degradable intracellular organics.

This strategy is particularly unwise for other reasons which include both the discharge of a highly turbid effluent and the presence of odors.

As a final point with respect to poor settling due to the presence of filaments, the SBR can be designed to operate efficiently with SVI's as great as 300 ml/g. In such cases the sludge blanket level need only be about 0.2 m below the final withdrawal point. For example, a sludge with an SVI of 300 ml/g and a MLSS of 2000 g/m^3 would occupy the bottom 60 percent of the tank volume after settling for 30 minutes. As was noted earlier, only 40% of the liquid volume was decanted during each cycle at Culver.

DESIGN CONSIDERATIONS

SBR design for an industrial wastewater would generally require an extensive treatability study and will not be discussed herein. Design for a domestic wastewater on the other hand is relatively simple and can be centered around the selection of the proper tank sizes, the inlet configuration, the outlet configuration, the aeration system and the control mechanism. The inlet, outlet and control mechanisms either have been sufficiently discussed earlier or should be selected logically by the designing engineer in accordance with the needs of the client. Tank sizing and aeration system selection are central to the proper design of the SBR and are considered below.

Tank Sizing

In a two tank system, the time for REACT, SETTLE, DRAW and IDLE (t_r, t_s, t_d and t_I respectively) for one tank must be equal to the time for FILL(t_f) for the other tank as is shown in Eq. (1).

$$t_f = t_r + t_s + t_d + t_I \qquad (1)$$

The FILL time, however, is equal to the volume available to be filled (V_f) divided by the volumetric flow rate, q, in m^3/d where:

$$V_f = V_{max} - V_o \qquad (2)$$

and $$t_f = V_f/q \qquad (3)$$

where V_{max} = the maximum liquid volume in one tank (m^3)

and V_o = the minimum (or initial) liquid volume at the beginning of FILL (m^3)

Similar equations must be developed for a three or more tank system by noting that the times for REACT, SETTLE, DRAW and IDLE for any one tank must be equal to the total FILL time for the remaining tanks in the system.

Eqs. (1), (2) and (3) can be used to calculate the tank sizes after selecting appropriate values for t_r, t_s, t_d and t_I. Of these t_s and t_d are the simplest for the sum of the two should probably be less than three

hours. For an industrial wastewater t_r must be determined from kinetic studies. For a domestic wastewater times ranging from 0.5 to 2 hours is likely sufficient. The remaining problem is to select t_I such that the SBR has the desired operating characteristics. Because the volumetric flow rate will vary with time, t_I will vary from cycle to cycle for each tank. The tank size that allows for some minimum acceptable IDLE time should be selected. This approach is easily extended to allow for a "negative" time in IDLE by including an overlap in FILL and DRAW in the design (i.e. FILL(1)).

The relationship between sludge age, mass loading and hydraulic detention time and tank sizing are not clear for the SBR because of the dramatic impact the aeration and mixing strategies have on overall performance. Nevertheless these are convenient terms, even though their definitions are not very obvious for the SBR, and are thus considered here.

The sludge age must be defined as the mass of solids present in the tanks divided by the mass of solids wasted each day. Because of the unsteady state nature of FILL and REACT a kinetic based definition is not possible. The SBR system at Culver operated at sludge ages that ranged from less than ten days to nearly 100 days without any apparent change in effluent quality. An interesting side-line to the sludge age in an SBR is its relationship to V_o, MLSS and SVI. As was noted earlier, an MLSS of 2000 g/m^3 with an SVI of 300 ml/g would result in a V_f of 0.4 times V_{max} (or V_o equal to 0.6 times V_{max}). This leads to a maximum mass of mixed liquor solids that can be held in any tank for a given MLSS and SVI which, in turn, leads to an upper bound on sludge age for a given V_o. As a result, tank sizing can be directly related to the desired sludge age and MLSS for any expected SVI.

Because the SBR has three non-aeration oriented functions (a portion of FILL and all of SETTLE, DRAW and IDLE), the definition of mass loading is obscure. A simple definition would involve the mass input of BOD_5 (in kg BOD_5/d) and the total mass of MLVSS (in kg) in the tanks. A more appropriate definition would include the fraction of time (f) the mixed liquor is under aeration each day as is shown in Eq. (4).

$$L = \frac{q\ S_o}{f\ V_T\ X_{max}} \qquad (4)$$

where L = mass loading (kg BOD_5/kg MLVSS-d)

q = average volumetric flow rate of the influent wastewater (m^3/d)

S_o = average BOD_5 concentration in the influent wastewater (gm/m^3)

f = average fraction of the total cycle time that the organisms are under aeration for all tanks (dimensionless)

V_T = maximum liquid volume in all tanks (m^3)

X_{max} = average organism concentration for all reactors at the end of FILL or REACT (g/m^3).

At Culver the average fraction of time the organisms were under aeration was approximately equal to 0.4. This resulted in a mass loading adjusted for aeration time of between 0.2 and 0.4 kg BOD_5/kg MLVSS-d. As with sludge age, mass loading can be used to select the total size of the SBR for any desired MLVSS. For loadings in this range and lower, the SBR is not stressed and acceptable effluent quality can be expected almost independent of loading.

The hydraulic detention time for the SBR can be based on any liquid volume ranging from the maximum to the minimum. At any time, the actual total liquid volume is between these two extremes. At Culver the average total detention time based on the maximum liquid volume ranged between 7 hours (during a day in March 1982 when the total flow through the plant was 3000 m^3/d) and 23 hours. Effluent quality during each of these extremes was essentially the same. In actuality a tank that serves as an equalization basin, reactor and clarifier cannot be associated easily with such a parameter as detention time. Neverthless the detention time can be used to estimate the total tank volume required.

Aeration System Selection

Jet aerators were used at Culver. The jets offered the convenience of providing mixing when the blowers were off and aeration when the blowers were on. With the exception of difficulties with the blowers during the first year, the jet aerators performed extremely well.

Separate recirculation pumps can be installed to provide periods of mixing. In that case any one of a variety of floating mechanical aerators or diffused air systems can be used for air supply. If neither denitrification nor biological phosphorus removal are required, the recirculation pumps can be eliminated entirely.

The maximum specific oxygen uptake rate to be expected for a domestic wastewater is approximately 40 g oxygen consumed/hr/kg MLVSS present. This rate would likely be possible almost any time after the first hour of FILL. For every 1000 m^3 of mixed liquor having a MLVSS concentration of 2000 g/m^3, this would correspond to an oxygen consumption rate of roughly 80 g/m^3-hr. As was noted earlier, this rate need not be met. A consumption rate of supplied oxygen of 40 g/m^3-hr would be satisfactory provided the remaining unreacted substrate were consumed during REACT. As a simple example, consider a four hour FILL period which includes 1.5 hours of aeration followed by one hour of aerated REACT for a tank containing 2000 kg of MLVSS. Using a consumption rate of 20 g/kg-hr during aerated FILL and 15 g /kg-hr during REACT , a total of 90 kg of oxygen would have been consumed. For a mass input rate of 1200 kg COD/d (4000 m^3/d at a COD of 300 g/m^3),

200 kg COD would have been added to the reactor during the 4 hour FILL period, leaving 110 kg of COD (roughly 80 kg of dry weight solids) to be discharged with the waste activated sludge. This corresponds to a net sludge yield of 0.4 kg MLVSS/kg COD removed (approximately 0.6 kg MLVSS/kg BOD_5, a reasonable number). Clearly the maximum oxygen consumption rate need not be met provided a reasonable COD balance can be maintained.

Operation and maintenance requirements, energy needs and total cost are all linked to the above calculation. Suppose, for example, the total aeration time were long enough that only 20 kg of solids COD (approximately 14 kg dry weight solids) accumulate each cycle. For a 2000 m^3 maximum liquid volume tank on a twelve hour cycle, this represents a 7 g/m^3 increase in the MLVSS each cycle or 14 g/m^3 each day. Assuming a daily accumulation rate for non-volatile solids of roughly double that, it would take 60 days for the MLSS to increase by 2500 g/m^3 (assuming no solids wasting). As a result, the system could be designed to allow sludge wasting once every 60 days. The energy requirements of this "large and lazy" system would be high but the sludge production and manpower needs low. Alternatively the aeration policy can be selected such that sludge production is maximized with sludge wasting taking place once each cycle. The energy requirements for this "small and active" system would be correspondingly lower but the manpower requirements would increase. As a result, a wide variety of cost/energy/ manpower considerations are possible with no unique combination obvious until confronted by a specific user.

OPERATION AND MAINTENANCE CONSIDERATIONS

Except for the automatic controller, all equipment used for an SBR is the same as that used for a conventional activated sludge plant less, of course, the sludge recycle system. The inlet and outlet devices are simply either pumps, valves or weirs. The aeration system is the same. The automatic controller can free the operator to devote more time to routine maintenance. If a "large and lazy" system is used, time consuming duties associated with sludge wasting are minimized. In Australia, fill and draw Pasveer ditches demand approximately one day of an operator's time each week. The treatment plant operator at Culver noted that the SBR was "more forgiving than the continuous flow system" that he had operated during his previous three years at Culver. If anything the SBR should require less time to operate than a conventional activated sludge system with about the same amount of time required for maintenance.

COST CONSIDERATIONS

General

Because Culver was a retrofit plant, limited information is available on capital costs. Except for efforts required for special analyses associated with the demonstration study and a reduction in energy usage associated with a more efficient aeration system (prior to the retrofit Culver utilized coarse bubble diffusers), the operation and maintenance costs were

essentially the same as for the continuous flow system. A new SBR (versus retrofit) would include features which would reduce overall operator requirements. Major cost saving features include the elimination of the secondary clarifier and associated sludge recycle system, and the inclusion of an automatic controller.

Cost Basis for the SBR

A modular design notion was used to estimate costs for daily flow rates of 379 m^3/d, 1893 m^3/d, 3785 m^3/d and 18,925 m^3/d. A two tank system was used for the 379 m^3/d plant and three tank systems for the remaining three daily flow rates. In all cases size selection was based on a 50 percent draw-off volume and a cycle with zero time in IDLE for peak flows at double the average dry weather flow. A summary of the times selected for each period is shown below.

TIME FOR EACH PERIOD (hr)

	Two Tanks		Three Tanks	
	Avg. Flow	Peak Flow	Avg. Flow	Peak Flow
FILL	4	2	2	1
REACT	2	0.5	2	0.5
SETTLE	0.75	0.75	0.75	0.75
DRAW	0.75	0.75	0.75	0.75
IDLE	0.5	0	0.5	0
TOTAL	8 hours	4 hours	6 hours	3 hours

Thus for each 3785 m^3/d of flow, each set of tanks in a two tank system has a volume of 1262 m^3 and each set of tanks in a three tank system, 631 m^3.

As an example of how this information can be used directly in estimating tank sizes, consider an average dry weather flow of 3200 m^3/d (this is roughly 84.5 percent of the 3785 m^3/d). For this flow the size of each tank for a two tank system would be 84.5 percent of 1262 m^3 or 1,067 m^3 and that for a three tank system 84.5 percent of 631 m^3 or 533 m^3. In this example the total volume of a two tank system is 2134 m^3 and that of a three tank system 1600 m^3. Interestingly a two tank system for the average flow used to design the Culver facility would have resulted in a total volume of 883 m^3 versus the 920 m^3 actually available.

Each set of tanks in the three tank system for the 18,925 m^3/d flow is assumed to have four tanks which operate in parallel. In all other cases only one tank in each set of tanks is assumed. This information is summarized below along with the total volume for each system.

Flow (m^3/d)	Sets	Tanks per Set	Total Volume (m^3)
379	2	1	252
1893	3	1	947
3785	3	1	1893
18,925	3	4	9465

The above specifications were then used to calculate excavation and backfill volumes, concrete qualities for the slab and walls, handrailings and other miscellaneous structures.

Capital costs are calculated using the relevant information in Table 10 plus specific cost information on floating mechanical aerators. Whenever specific cost information was used the installed equipment cost was estimated at 1.5 times the list price. In all cases the various unit prices and cost indices were projected (from data available through May 1982) for January 1983. The present worth cost factor was based on an interest rate of 7 3/8 percent and a 20 year life. CAPDET (43) (Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems) was used to estimate operation and maintenance costs.

Capital Cost of the SBR

In Section 4 SBR costs are compared with those for the oxidation ditch and conventional activated sludge (see Tables 13, 14, 15 and 16). The comparative analysis includes costs for raw sewage pumping, preliminary treatment, chlorination and sludge handling systems. Table 11 summarizes cost estimates for all components required for operation of the SBR tank only for the four average daily flow rates discussed above. In all cases the submersible pumps were eliminated from the analysis because their inclusion would have little or no impact on BOD_5 and SS removal efficiency and would add between 10 and 13 percent to total installed capital costs. This is a significant savings and should be considered seriously for any system not requiring either denitrification or biological phosphorus removal. If mixing is required, costs savings may be possible by using jet aerators instead of a floating mechanical aerator, submersible pump combination. A floating aerator system was selected, however, to demonstrate the utility of more commonly used hardware in SBR design. In addition it provides a better basis for comparison with the equivalent conventional technologies described in the next section.

While the modular design notion provides reasonable costs for the three lower flow rate systems, this approach results in unreasonable costs for the 18,925 m^3/d facility. In particular any appreciable economy of scale is lost with respect to items such as the inlet and discharge structures and excavation and concrete work. A more aggressive approach to innovative design in this area would likely result in a savings of roughly $200,000.

Table 10. UNIT PRICES AND COSTS INDICES

Building	75.00	$/SQFT
Excavation	3.50	$/CUYD
Wall Concrete	350.00	$/CUYD
Slab Concrete	200.00	$/CUYD
Marshall and Swift Index	760.00	
Crane Rental	100.00	$/HR
EPA Construction Cost Index	190.00	
Canopy Roof	20.00	$/SQFT
Labor Rate	15.00	$/HR
Operator Class II	10.00	$/HR
Electricity	0.06	$/KWHR
Chemical Costs		
Lime	0.05	$/LB
Alum	0.06	$/LB
Iron Salts	0.09	$/LB
Polymer	3.00	$/LB
Engineering News Record Cost Index	4000.00	
Handrail	30.00	$/FT
Pipe Cost Index	400.00	
Pipe Installation Labor Rate	18.00	$/HR
Eight Inch Pipe	12.30	$/FT
Eight Inch Pipe Bend	117.64	$/UNIT
Eight Inch Pipe Tee	174.11	$/UNIT
Eight Inch Pipe Valve	1824.07	$/UNIT

TABLE 11. COST ESTIMATES FOR SBR FOR FOUR AVERAGE DAILY FLOW RATES

Process Unit	Flow Rates (m^3/d)			
	379	1893	3785	18,925
Inlet Control System	$2,000	$3,000	$4,000	$20,000
Contact Chamber Baffle Walls	2,000	4,000	5,000	24,000
Aerators	25,000	50,000	60,000	256,000
Excavation, Concrete and Handrail	70,000	150,000	250,000	840,000
Microprocessors	10,000	10,000	10,000	10,000
Level Control/Monitoring	2,000	4,000	4,000	16,000
Decant System	9,000	16,000	18,000	90,000
Subtotal (1)+	$120,000	$237,000	$351,000	$1,256,000
Noncomponent Costs*	30,000	59,000	88,000	314,000
Subtotal (2)	$150,000	$296,000	$439,000	$1,570,000
Engineering, Construction on Supervision and Contingencies**	45,000	89,000	132,000	471,000
Total Installed Capital Costs	$195,000	$385,000	571,000	$2,041,000
Annual Operation and Maintenance Costs	13,000	24,000	40,000	148,000
Present Worth Costs***	$329,000	$632,000	$983,000	$3,564,000

+Included in SBR columns of Tables 13, 14, 15 and 16 as Aeration/Clarification.

*At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

**At 30 percent of subtotal (2).

***Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

Operation and Maintenance Costs of the SBR

Operation and Maintenance (O & M) costs are summarized in Table 11. These costs were estimated from calculated power usages per year for the installed equipment and a review of O & M costs obtained from CAPDET (43) for the same flow rates for a corresponding oxidation ditch. The oxidation ditch was selected for direct comparison for three reasons. First, a fill and draw form of the oxidation ditch has been successfully operated in parts of Europe and throughout New South Wales, Australia. Second, the SBR can operate without primary sedimentation and with aerobic digestion built into standard operation (e.g. by aeration during IDLE and during as long as possible throughout FILL without developing poor settling characteristics). Third, effluent quality from the SBR is similar to that of the oxidation ditch. As a result, both systems are being compared for the "same job". On the other hand a conventional completely mixed activated sludge plant historically has not performed as well as the oxidation ditch. A summary of these O & M costs is presented in Table 12.

ENERGY CONSIDERATIONS

General

Power consumption at Culver can be broken down as follows:

Item	% Total SBR Power Consumption
Mixing	49
Aeration (blowers)	40
Decanting	10
Chlorination	1
Total	100

Estimated energy consumption values, in kWh/d, from November 1980 through February 1981 are presented below.

	NT	ST	TOTAL
NOV	198	179	377
DEC	204	175	379
JAN	203	191	394
FEB	177	168	345
AVG	196	178	374

TABLE 12. OPERATION AND MAINTENANCE COST ESTIMATES FOR THE SBR FOR FOUR AVERAGE DAILY FLOW RATES

Costs (dollar/yr)*	Flow Rates (m^3/d)			
	379	1893	3785	18,925
Operation Labor	$ 7,855	$10,046	$15,518	$33,208
Maintenance Labor	1,319	1,941	2,346	5,062
Power**	2,232	9,660	18,900	96,600
Material	1,890	2,640	3,722	13,136
TOTAL O & M (rounded)	$13,000	$24,000	$40,000	$148,000

* Except for power costs all estimates are from CAPDET (42).

** Includes mixing, aeration and decanting at a power rate of $0.06/kWh.

This power consumption of 374 kWh/d (13.7×10^4 kWh/yr) could easily have been reduced to approximately 300 kWh/d (150 kWh/d per tank or 11×10^4 kWh/yr) by eliminating some or replacing (with lower power pumps) all of the jet aerators without exceeding the effluent limitations of 10 g/m^3 BOD_5 and 10 g/m^3 SS. This would result in a yearly energy requirement of 11×10^4 kWh/r. More energy would have to be supplied for nitrification if that were an effluent limitation for discharge.

Energy Requirements

Estimated energy requirements for aeration and decanting are summarized below for each of the SBR systems discussed.

	Energy Requirements (kWh/yr)		
Flow rate (m^3/d)	Aeration	Decanting	Total
379	33.1×10^3	4.1×10^3	37.2×10^3
1893	12.4×10^4	3.7×10^4	16.1×10^4
3785	24.9×10^4	6.6×10^4	31.5×10^4
18,925	12.4×10^5	3.7×10^5	16.1×10^5

The estimated total energy usage for the 1893 m^3/d system is 1.2 times the average yearly rate of energy usage recorded at Culver between November 1980 and February 1981 (or 1.5 times, if the lower power pump value is used) for a flow that is 1.4 times the average Culver flow during that period. A final point worth noting is that each aerator was assumed to operate 15 hours each day or 62.5 percent of the time. This is a conservative assumption especially since the aeration system at Culver operated only 40 percent of the time.

SECTION 4

COMPARISON WITH EQUIVALENT TECHNOLOGY

GENERAL

The Culver demonstration plant (1), a U.S. EPA demonstration study involving the retrofit of a conventional activated sludge treatment facility with a design flow of 1135 m^3/d (0.3 MGD), is the only full-scale SBR in operation today that treats a domestic wastewater. Fill and draw versions of the oxidation ditch have operated successfully in both Europe and Australia. As a result, cost and energy comparisons were limited to conventional activated sludge and the oxidation ditch even though the SBR can be made to operate with features similar to any of the many suspended growth activated sludge treatment options on the market today.

Because of the rather limited information available on the SBR, the cost and energy estimates for the SBR were conservative and do not necessarily reflect the full potential of this innovative technology. For example, each floating mechanical aerator was assumed to be operational fifteen hours each day instead of a more likely (but less conservative) twelve hours each day. This 25 percent in aeration time increased, markedly, the estimated energy requirements. In addition, the sludge produced from the SBR was assumed to be in a state of stabilization intermediate to that which would be produced from a conventional activated sludge plant and an oxidation ditch even though the fifteen hours of aeration would likely result in a sludge similar to that of the oxidization ditch. The effect of this assumption was translated into both higher costs and energy usage for sludge handling, primarily because of the selection of aerobic digestion for comparison with the oxidation ditch.

COST COMPARISONS

Cost summaries comparing the SBR with the oxidation ditch alone is presented in Table 13 and with conventional activated sludge and the oxidation ditch, in Tables 14, 15, and 16. Except for the entry for the SBR in the process unit described as Aeration/Clarification and the O & M costs corresponding to the same category, all costs through subtotal (1) in these Tables were obtained from CAPDET (43). The SBR entry for these tables was obtained from subtotal (1) in Table 11. The SBR entry for Annual Operation and Maintenance Costs was obtained by adding the equivalent entry from Table 11 to CAPDET O & M costs for all other process units. Except for costs associated with mechanical aeration energy requirements all other O &

TABLE 13. COST COMPARISON - 379 m^3/d FACILITY

Process Unit	Oxidation Ditch	SBR
Raw Sewage Pumping	$40,000	$40,000
Preliminary Treatment	24,000	24,000
Aeration/Clarification (see Table 11)	240,000	120,000
Chlorination	48,000	48,000
Aerobic Digestion	--	40,000
Sludge Lagoons	7,000	7,000
Subtotal (1)	$359,000	$279,000
Noncomponent Costs*	90,000	70,000
Subtotal (2)	$449,000	$349,000
Engineering, Construction Supervision and Contingencies**	135,000	105,000
Total Installed Capital Cost	$584,000	$454,000
Annual Operation and Maintenance Costs	65,000	58,000
Present Worth Costs***	$1,253,000	$1,051,000

*At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

**At 30 percent of subtotal (2).

***Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

TABLE 14. COST COMPARISON - 1893 m^3/d FACILITY

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	$248,000	$248,000	$248,000
Preliminary Treatment	36,000	36,000	36,000
Primary Clarification	128,000	-	-
Aeration/Clarification (see Table 11)	448,000	416,000	237,000
Chlorination	80,000	80,000	80,000
Gravity Thickening	64,000	64,000	64,000
Aerobic Digestion	208,000	152,000	208,000
Vacuum Filtration	272,000	272,000	272,000
Sludge Lagoons	12,000	12,000	12,000
Chemical Feed Systems	44,000	44,000	44,000
Subtotal (1)	$1,540,000	$1,324,000	$1,201,000
Noncomponent Costs*	385,000	331,000	300,000
Subtotal (2)	$1,925,000	$1,655,000	$1,501,000
Engineering, Construction Supervision and Contingencies**	578,000	497,000	450,000
Total Installed Capital Costs	$2,503,000	$2,152,000	$1,951,000
Annual Operation and Maintenance Costs	166,000	150,000	150,000
Present Worth Costs***	$4,212,000	$3,696,000	$3,495,000

*At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

**At 30 percent of subtotal (2).

***Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

TABLE 15. COST COMPARISON - 3785 m^3/d FACILITY

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	$312,000	$312,000	$312,000
Preliminary Treatment	56,000	56,000	56,000
Primary Clarification	164,000	-	-
Aeration/Clarification (see Table 11)	624,000	576,000	351,000
Chlorination	104,000	104,000	104,000
Gravity Thickening	68,000	68,000	68,000
Aerobic Digestion	264,000	160,000	264,000
Vacuum Filtration	288,000	272,000	288,000
Sludge Handling and Landfilling	76,000	68,000	76,000
Chemical Feed Systems	44,000	44,000	44,000
Subtotal (1)	$2,000,000	$1,660,000	$1,563,000
Noncomponent Costs*	500,000	415,000	391,000
Subtotal (2)	$2,500,000	$2,075,000	$1,954,000
Engineering, Construction Supervision and Contingencies**	750,000	623,000	586,000
Total Installed Capital Costs	$3,250,000	$2,698,000	$2,540,000
Annual Operation and Maintenance Costs	230,000	190,000	190,000
Present Worth Costs***	$5,617,000	$4,654,000	$4,496,000

*At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

**At 30 percent of subtotal (2).

***Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

TABLE 16. COST COMPARISON - 18,925 m^3/d FACILITY

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	$600,000	$600,000	$600,000
Preliminary Treatment	148,000	148,000	148,000
Primary Clarification	352,000	-	-
Aeration/Clarification (see Table 11)	1,720,000	1,952,000	1,256,000
Chlorination	160,000	160,000	160,000
Gravity Thickening	88,000	88,000	88,000
Aerobic Digestion	624,000	256,000	624,000
Vacuum Filtration	496,000	280,000	496,000
Sludge Handling and Landfilling	88,000	72,000	88,000
Chemical Feed Systems	56,000	44,000	56,000
Subtotal (1)	$4,332,000	$3,600,000	$3,516,000
Noncomponent Costs*	1,083,000	900,000	879,000
Subtotal (2)	$5,415,000	$4,500,000	$4,395,000
Engineering, Construction Supervision and Contingencies**	1,625,000	1,350,000	1,319,000
Total Installed Capital Costs	$7,040,000	$5,850,000	$5,714,000
Annual Operation and Maintenance Costs	490,000	455,000	455,000
Present Worth Costs***	$12,083,000	$10,533,000	$10,397,000

*At 25 percent of subtotal (1), includes piping, electrical, instrumentation and site preparation.

**At 30 percent of subtotal (2).

***Present worth computed at 7 3/8 percent interest rate and 20 year life (PWF = 10.29213). Add present worth O & M costs to Total Installed Capital Costs.

M costs were estimated from CAPDET (see explanation below). As was noted for Table 11, CAPDET was updated to include estimated costs for January 1983. The SBR was not compared with conventional activated sludge for the 379 m^3/d flow because it was felt that a comparison in that flow range would be inappropriate.

ENERGY COMPARISONS

Electrical energy requirements in kWh/yr for the 379 m^3/d plant are summarized below. Note that energy for building heating, lights and miscellaneous would be approximately the same for each flow rate.

Process Unit	Oxidation Ditch	SBR
Preliminary Treatment	0.9×10^3	0.9×10^3
Aeration/Clarification/ Decant	42.0×10^3	37.2×10^3
Chlorination	5.0×10^3	5.0×10^3
TOTAL	47.9×10^3	43.1×10^3

Estimates for Aeration/Clarification/Decant for the SBR are from Section 3 which assumed a 15 hour aeration time for each aerator. Estimates for mechanical aeration energy requirements for the aeration tank and the aerobic digesters were obtained from Wesner, Culp, Lineck and Hinrichs (44) because of the high values calculated from CAPDET. All other energy requirements were obtained from CAPDET.

Tables 17, 18 and 19 summarize energy comparisons for the three systems for the three higher flow rates. The data for these tables was obtained in the same manner as was described for the 379 m^3/d flow rate.

Before closing this section, two other energy saving features should be mentioned. First, the withdraw mechanism will utilize essentially no energy if a gravity system is used. Pump motivated decanting was assumed above. Second, the control mechanism can be easily interfaced with a D.O. probe so that aerator use can be optimized. This feature was recently added to the microprocessor control system at Culver.

TABLE 17. ENERGY COMPARISON (kWh/yr) - 1893 m^3/d FACILITY

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	4.9×10^4	4.9×10^4	4.9×10^4
Preliminary Treatment	1.2×10^4	1.2×10^4	1.2×10^4
Primary Clarification	0.8×10^4	-	-
Aeration/ Clarification/Decant	8.5×10^4	25.0×10^4	16.1×10^4
Chlorination	0.5×10^4	0.5×10^4	0.5×10^4
Gravity Thickening	0.3×10^4	0.3×10^4	0.3×10^4
Aerobic Digestion	12.0×10^4	1.0×10^4	5.0×10^4
Vacuum Filtration	0.9×10^4	0.5×10^4	0.9×10^4
TOTAL	29.1×10^4	33.4×10^4	28.9×10^4

TABLE 18. ENERGY COMPARISONS (kWh/yr) - 3785 m^3/d (1 MGD) FACILITY

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	9.5×10^4	9.5×10^4	9.5×10^4
Preliminary Treatment	1.6×10^4	1.6×10^4	1.6×10^4
Primary Clarification	0.8×10^4	-	-
Aeration/ Clarification/Decant	20.0×10^4	41.0×10^4	31.5×10^4
Chlorination	0.7×10^4	0.7×10^4	0.7×10^4
Gravity Thickening	0.4×10^4	0.4×10^4	0.4×10^4
Aerobic Digestion	22.0×10^4	1.2×10^4	9.0×10^4
Vacuum Filtration	1.8×10^4	0.4×10^4	1.8×10^4
Sludge Handling and Landfilling	9.0×10^4	9.0×10^4	9.0×10^4
TOTAL	65.8×10^4	63.8×10^4	63.5×10^4

TABLE 19. ENERGY COMPARISON (kWh/yr) - 18,925 m^3/d FACILITY

Process Unit	Conventional Activated Sludge	Oxidation Ditch	SBR
Raw Sewage Pumping	4.2×10^5	4.2×10^5	4.2×10^5
Preliminary Treatment	0.3×10^5	0.3×10^5	0.3×10^5
Primary Clarification	0.1×10^5	-	-
Aeration/ Clarification/Decant	9.0×10^5	25.0×10^5	16.1×10^5
Chlorination	0.1×10^5	0.1×10^5	0.1×10^5
Gravity Thickening	0.1×10^5	0.1×10^5	0.1×10^5
Aerobic Digestion	12.0×10^5	0.6×10^5	5.0×10^5
Vacuum Filtration	0.8×10^5	0.2×10^5	0.8×10^5
Sludge Handling and Landfilling	3.5×10^5	3.5×10^5	3.5×10^5
TOTAL	30.1×10^5	34.0×10^5	30.1×10^5

SECTION 5

NATIONAL IMPACT ASSESSMENT

MARKET POTENTIAL

According to the "1978 Needs Survey for Conveyance and Treatment of Municipal Wastewaters," 67.1 percent of the 9,941 wastewater treatment plants in use at the time of report preparation were of the activated sludge type. These plants handled 84.1 percent of the 112,185 m^3/d of wastewater flow being treated at that time. A similar profile was reported for both the 920 treatment facilities under construction and the some 7,775 estimated to be required between 1978 and 2000. Specifically 71.9 percent of those being constructed and 85.8 percent of those expected to be built were activated sludge systems of one form or another and these were estimated to treat 82.9 percent and 81.2 percent of the additional flow respectively. Clearly activated sludge is the system of choice for present and future users.

The average daily flow for the 7775 additional treatment plants to be required by the year 2000 is 6,320 m^3/d. Because the SBR is a time oriented activated sludge system that operates extremely well at or about this flow rate and because of the excellent performance of the U.S. EPA Demonstration Study at Culver (1), the market potential for the SBR is believed to be quite good. In addition, the exposure of the SBR during the past several years has been high especially as a result of a series of emerging technology seminars presented by the U.S. EPA and the American Consulting Engineers Council at all ten U.S. EPA regions between March and May 1982.

COST AND ENERGY IMPACT

The cost and energy comparisons presented in Tables 13 through 19 are quite encouraging even though considerable additional data must be accumulated before more reliable estimates can be made. Of particular interest was the close comparison between the SBR and the oxidation ditch. No discernible difference between the two systems could be observed as evaluated, the estimates being within the accuracy of the estimating procedure. In addition the reliability and consistency of effluent quality for the SBR at Culver was excellent and certainly comparable to that reported for the oxidation ditch.

An interesting feature of the SBR is that the energy input can be varied over a rather wide range without seriously impairing the effluent quality. This benefit results from the fill and draw nature of the system and probably cannot be matched by most continuous flow activated sludge systems.

Based on the cost and energy results reported herein and the obvious flexibility of the SBR, the potential for the SBR penetration in both present and future markets is expected to be quite high. The extent of penetration however, will depend upon actual costs and energy needs of the first group of new SBR facilities to be constructed and operated.

RISK ASSESSMENT

The SBR is a new technology that will be more foreign to potential users in the United States than will most all other new technologies because it is not a continuous flow system. Until the novelty of periodic operation becomes accepted as a viable treatment alternative, implementation of the SBR will be slow. In addition because it is a new technology, the SBR will likely be misused by individuals not realizing its limitations or not understanding the SBR well enough to design the system properly. Finally, sewage treatment plant operators are not familiar with fill and draw operation and, as a result, will require special training. In spite of these potential difficulties, the net benefits expected from the SBR outweigh any potential risk from the system.

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